

A Large Range of Correlation Measurements with PHOBOS

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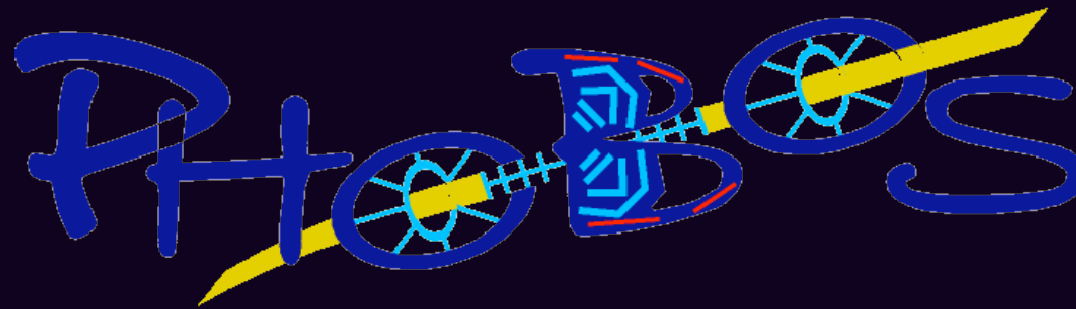
Workshop on the “Ridge”, BNL, September 22-24, 2008

RHIC has always had a Ridge nearby



PHOBOS Collaboration

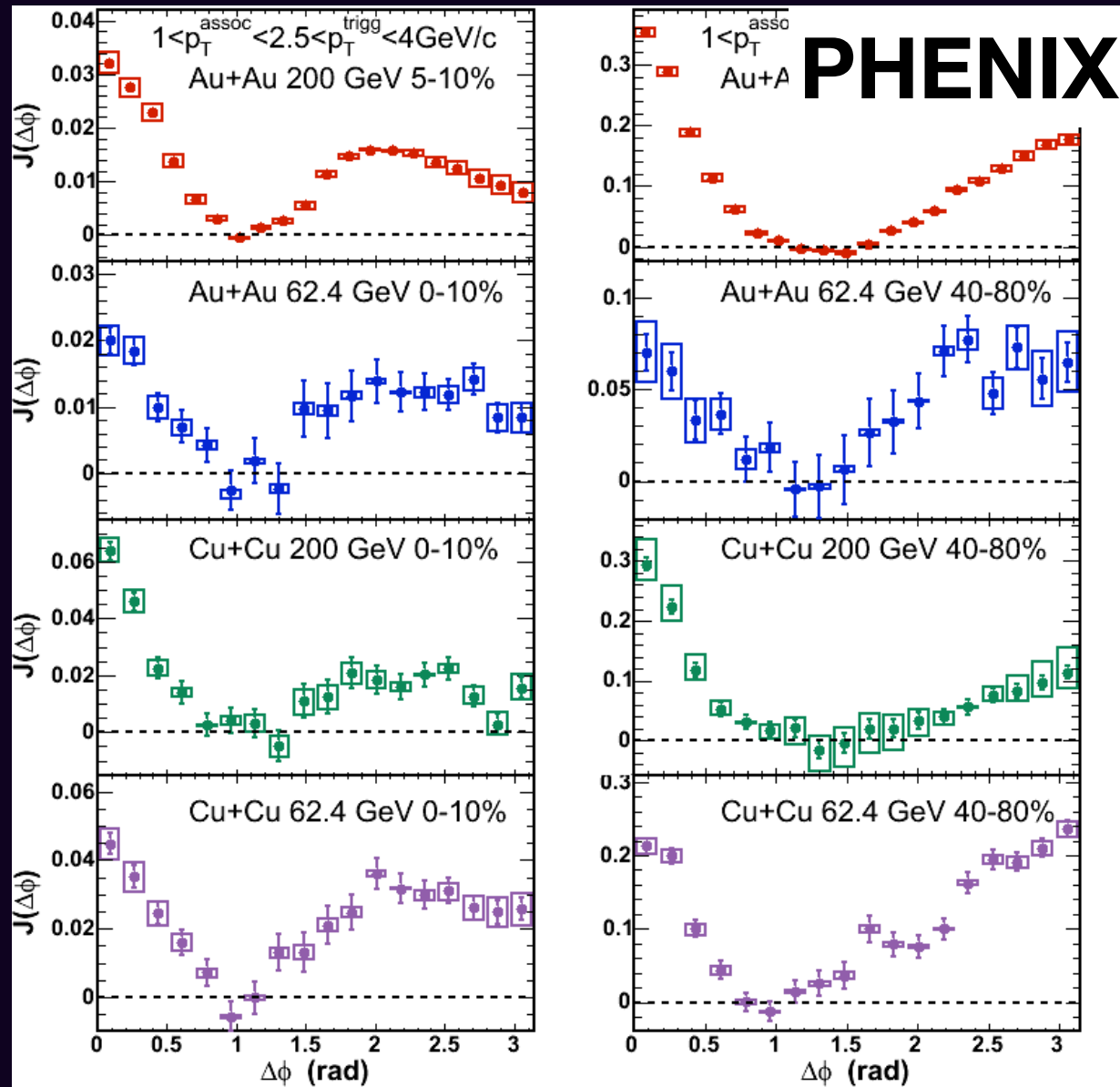
Burak Alver, Birger Back, Mark Baker, Maarten Ballintijn, Donald Barton, Russell Betts, Richard Bindel, Wit Busza (Spokesperson), Vasundhara Chetluru, Edmundo García, Tomasz Gburek, Joshua Hamblen, Conor Henderson, David Hofman, Richard Hollis, Roman Hołyński, Burt Holzman, Aneta Iordanova, Chia Ming Kuo, **Wei Li**, Willis Lin, Constantin Loizides, Steven Manly, Alice Mignerey, Gerrit van Nieuwenhuizen, Rachid Nouicer, Andrzej Olszewski, Robert Pak, Corey Reed, Christof Roland, Gunther Roland, Joe Sagerer, Peter Steinberg, George Stephans, Andrei Sukhanov, Marguerite Belt Tonjes, Adam Trzupek, Sergei Vaurynovich, Robin Verdier, Gábor Veres, Peter Walters, **Edward Wenger**, Frank Wolfs, Barbara Wosiek, Krzysztof Woźniak, Bolek Wyslouch



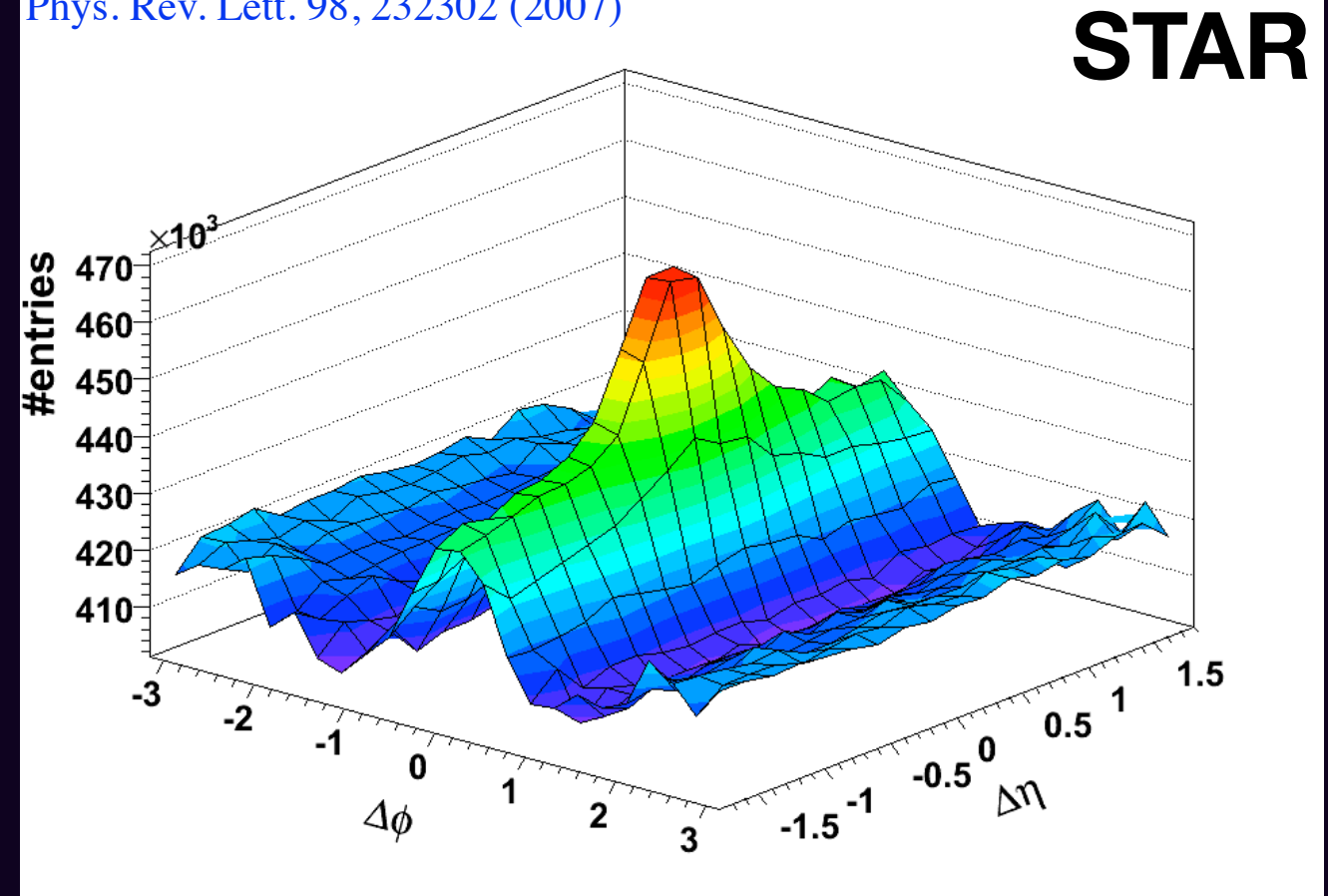
ARGONNE NATIONAL LABORATORY, BROOKHAVEN NATIONAL LABORATORY
INSTITUTE OF NUCLEAR PHYSICS PAN, KRAKOW, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
NATIONAL CENTRAL UNIVERSITY, TAIWAN, UNIVERSITY OF ILLINOIS AT CHICAGO
UNIVERSITY OF MARYLAND, UNIVERSITY OF ROCHESTER

Triggered Correlations

Motivation: Nuclear Modifications



Phys. Rev. Lett. 98, 232302 (2007)



Away side strongly modified
in central Au+Au & Cu+Cu
at all energies (the “cone”)

Near side correlations
highly extended in η
in Au+Au collisions
(the “ridge”)

Explanations of the Ridge

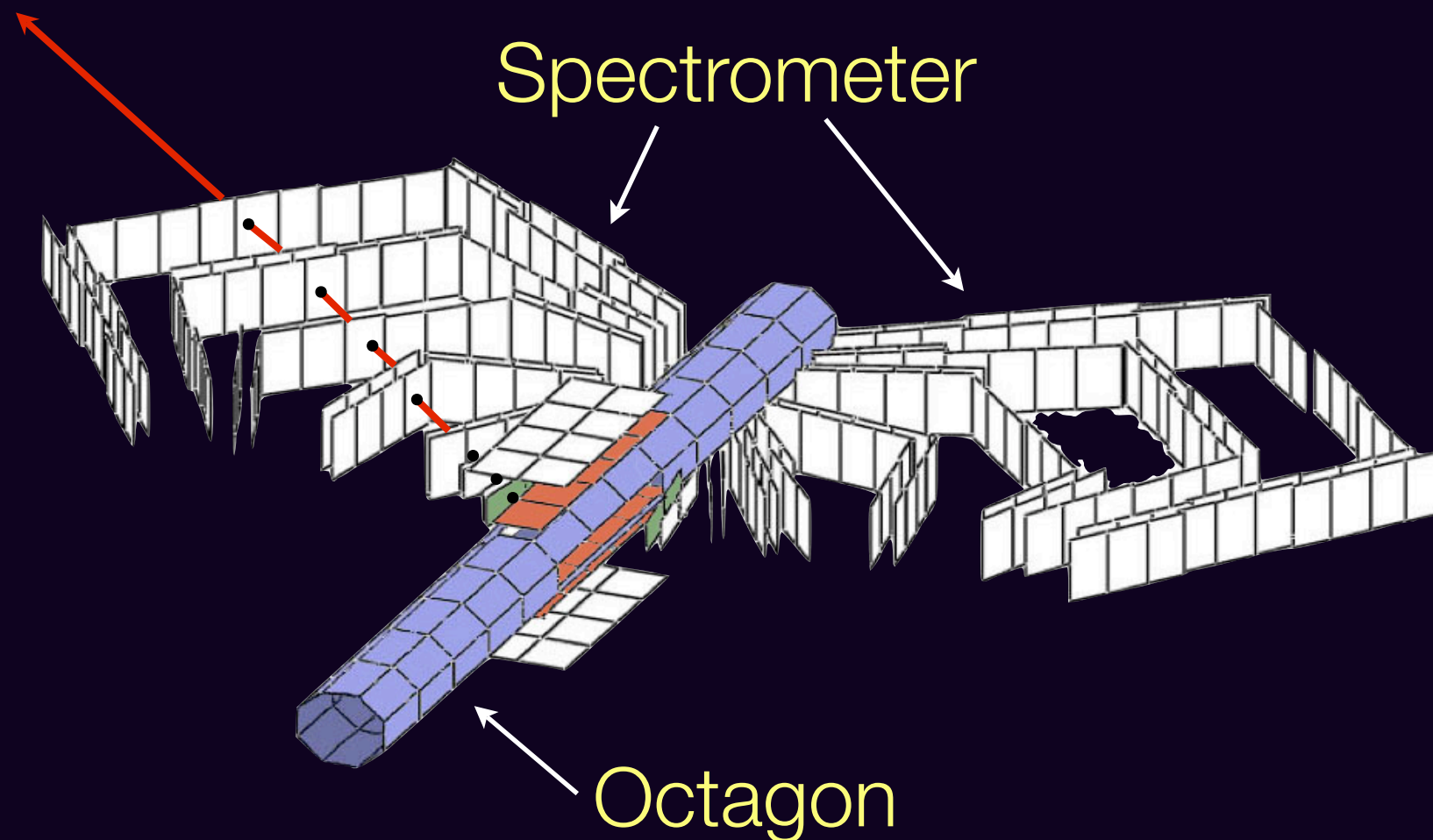
Various hypotheses proposed to explain ridge phenomenon

- **Coupling of induced radiation to longitudinal flow**
Armesto et al., PRL 93, 242301
- **Recombination of shower + thermal partons**
Hwa, arXiv:nucl-th/0609017v1
- **Anisotropic plasma**
Romatschke, PRC 75, 014901
- **Turbulent color fields**
Shuryak, arXiv:0706.3531v1
- **Bremsstrahlung + transverse flow + jet-quenching**
Majumder, Muller, Bass, arXiv:hep-ph/0611135v2
- **Splashback from away-side shock**
Pantuev, arXiv:0710.1882v1
- **Momentum kick imparted on medium partons**
Wong, arXiv:0707.2385v2
- **Glasma Flux Tubes**
Dumitru, Gelis, McLerran, Venugopalan, arXiv:0804.3858; Gavin, McLerran, Moscelli, arXiv:0806.4718

The PHOBOS contribution: large acceptance for associated yield

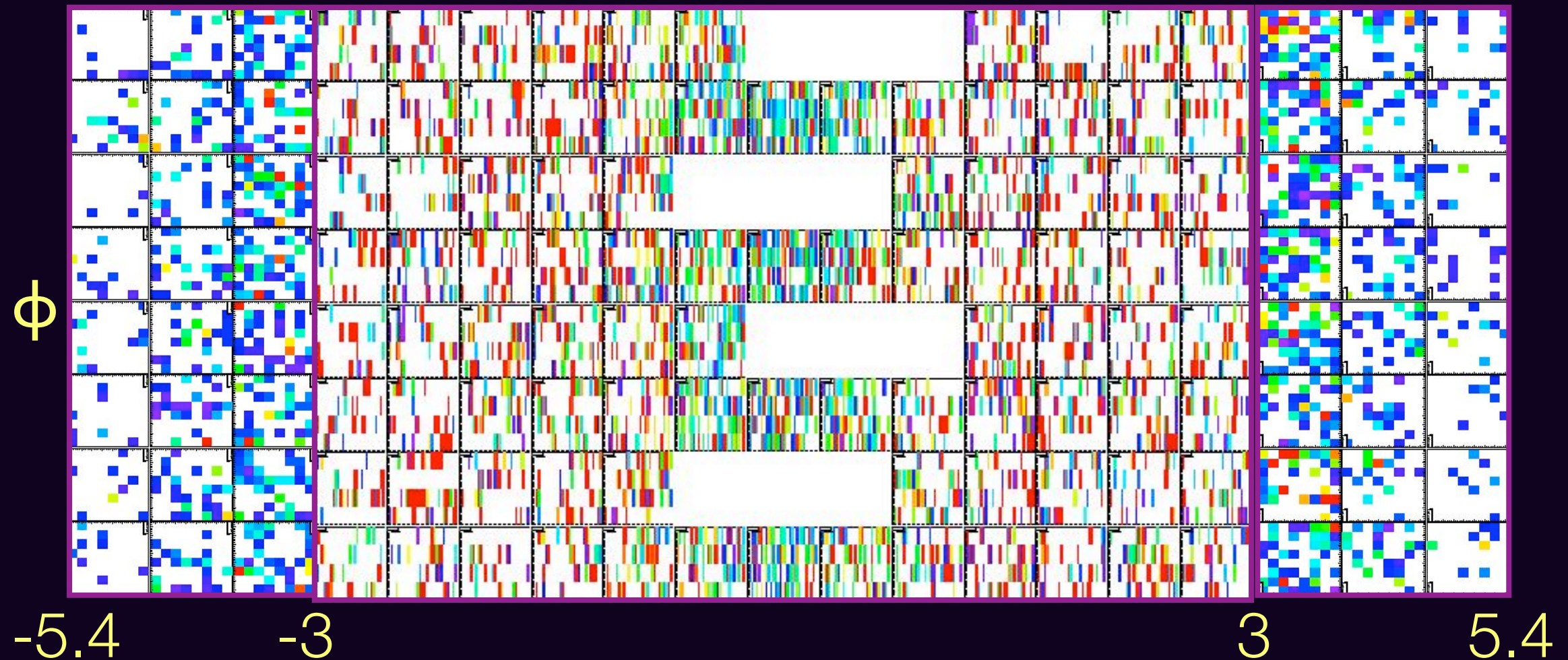
Triggered Correlations in PHOBOS

PHOBOS uses its two main subsystems



While spectrometer has small ϕ acceptance, it has a large ($\Delta\eta \sim 1.5$) forward acceptance ($\langle\eta\rangle \sim 0.8$)

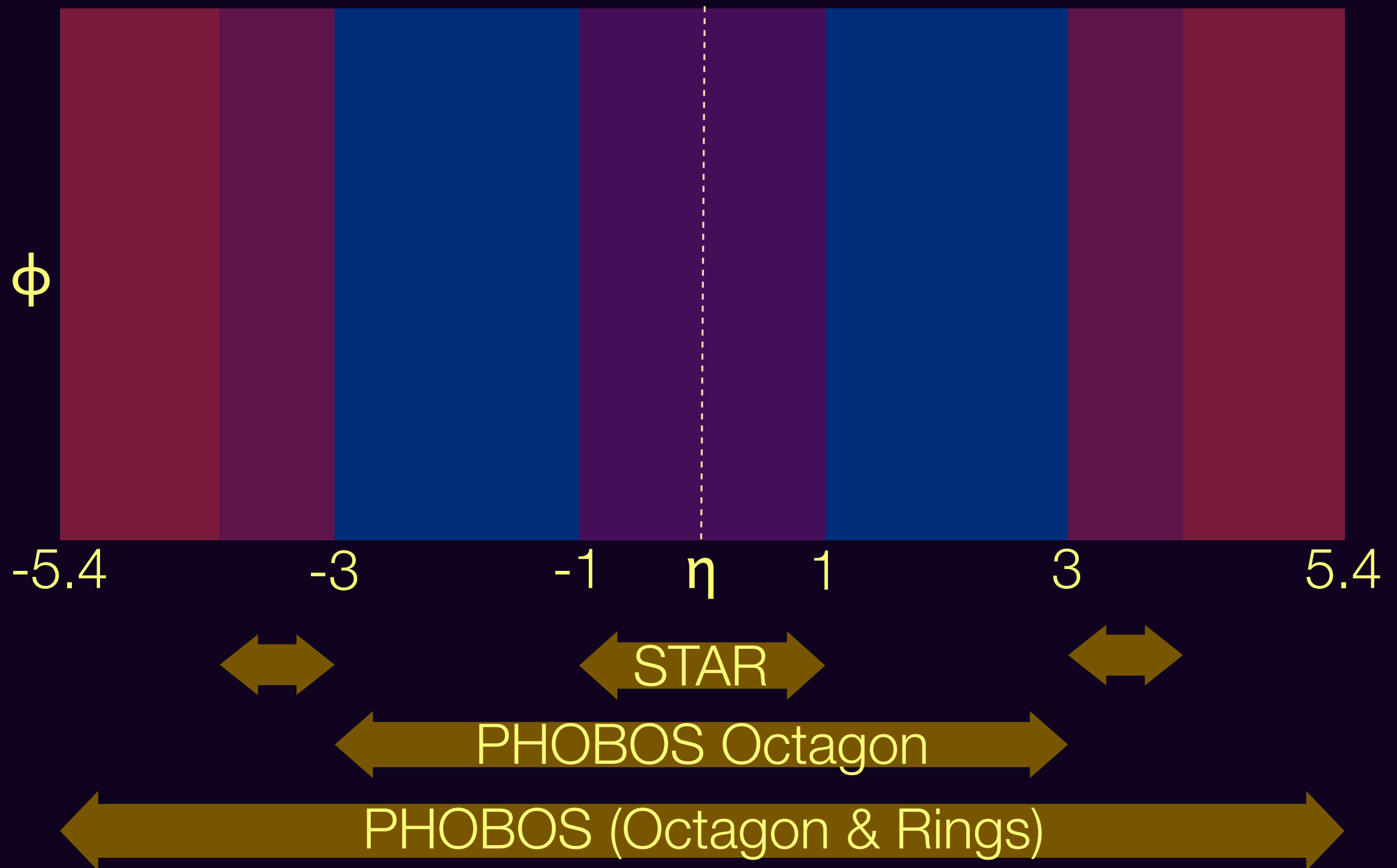
PHOBOS Multiplicity Acceptance



Pros: nearly-full azimuthal acceptance for associated particles
nearly-full pseudorapidity acceptance ($|\eta| < 5.4$)

Cons: no momentum measurement, no particle ID

PHOBOS Acceptance



Not yet using full potential of PHOBOS, but smaller systematics

Constructing Correlation Function

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{ch}}}{d\Delta\phi d\Delta\eta} = S(\Delta\phi, \Delta\eta) - B(\Delta\phi, \Delta\eta) \cdot a [1 - 2V(\Delta\eta) \cos(2\Delta\phi)]$$

$$= B(\Delta\eta) \left\{ \frac{s(\Delta\phi, \Delta\eta)}{b(\Delta\phi, \Delta\eta)} - a [1 + 2V(\Delta\eta) \cos(2\Delta\phi)] \right\}$$

Acceptance corrected
mixed-event pairs (per
trigger)

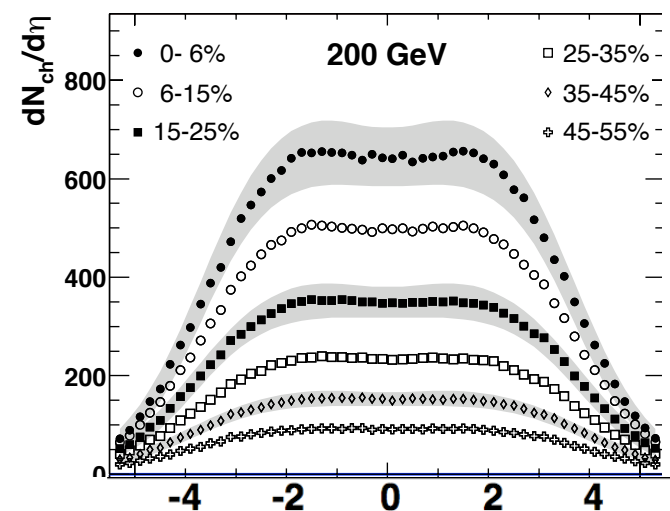
Signal/Background
Detector acceptance
cancels in the ratio

Modulation from
elliptic flow

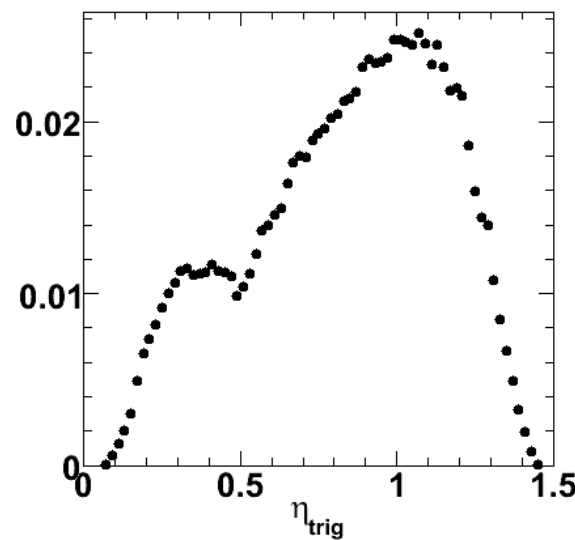
$$V = \langle v_2^{\text{trig}} \rangle \langle v_2^{\text{assoc}} \rangle$$

Calculating the Background

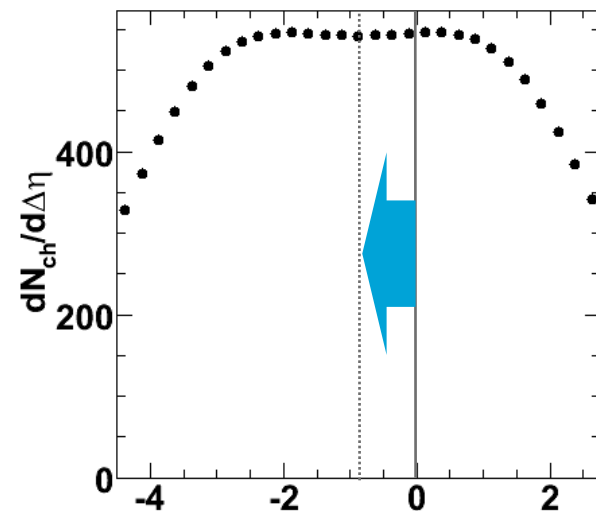
- **$B(\Delta\eta)$** is the per trigger mixed-event pair distribution corrected for the pair acceptance
- In other words, it is the corrected single-particle distribution ($dN/d\eta$) convoluted with η_{trig}



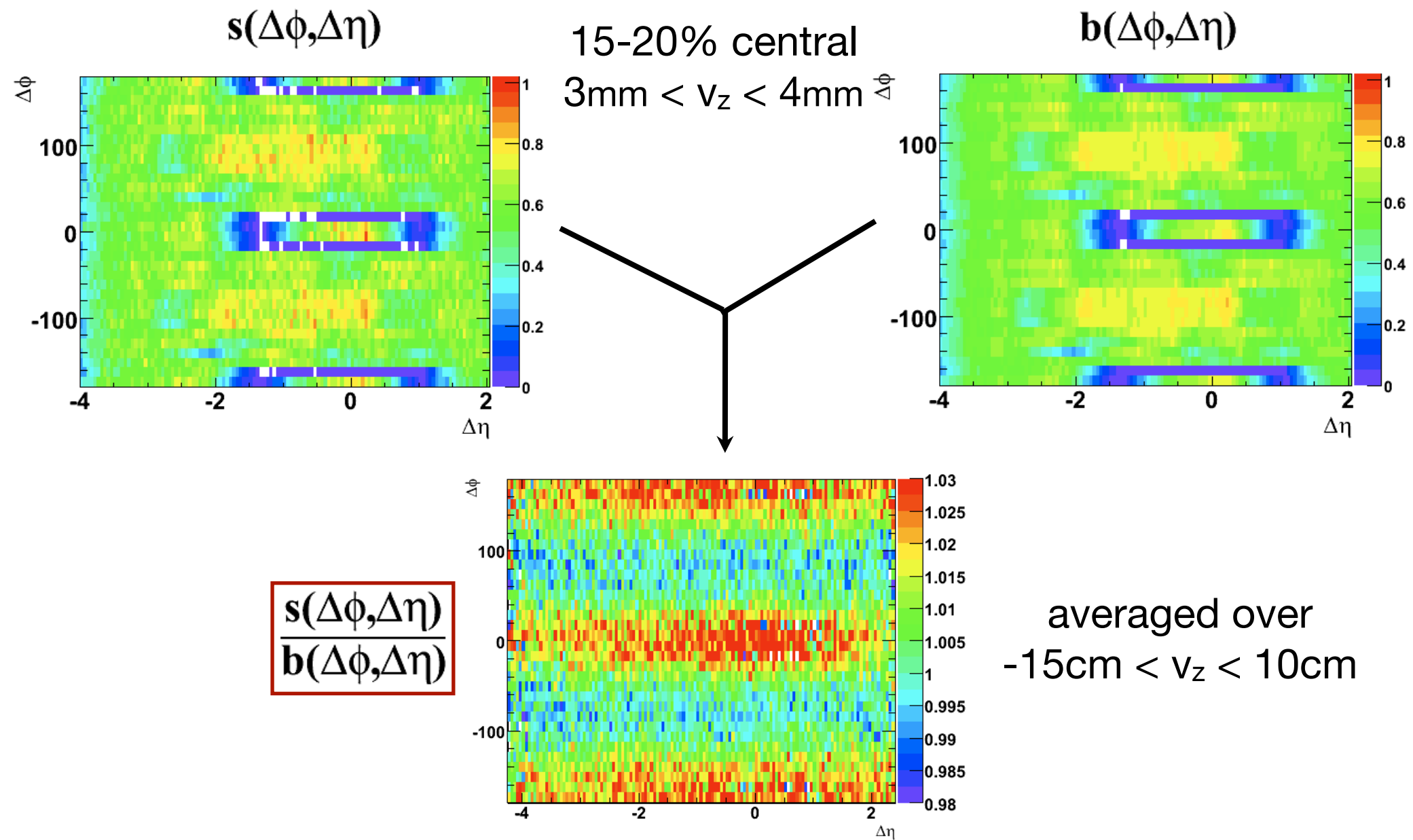
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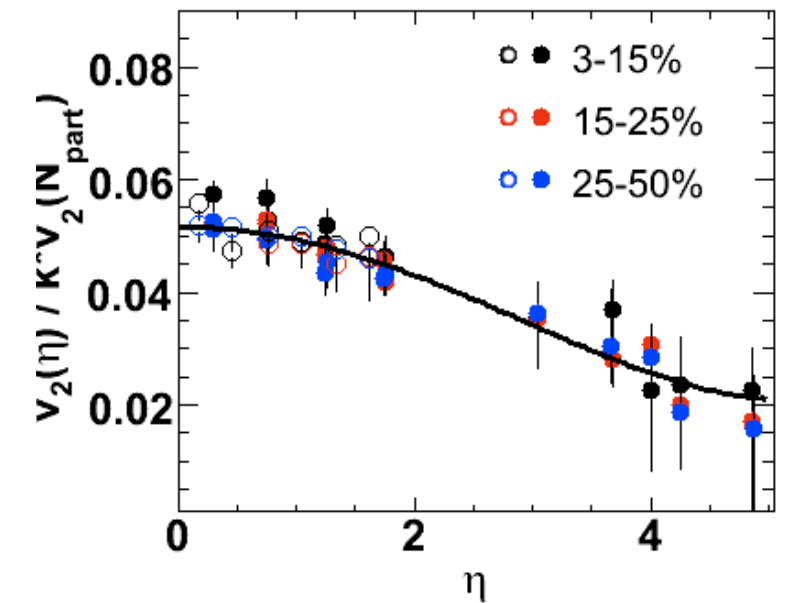
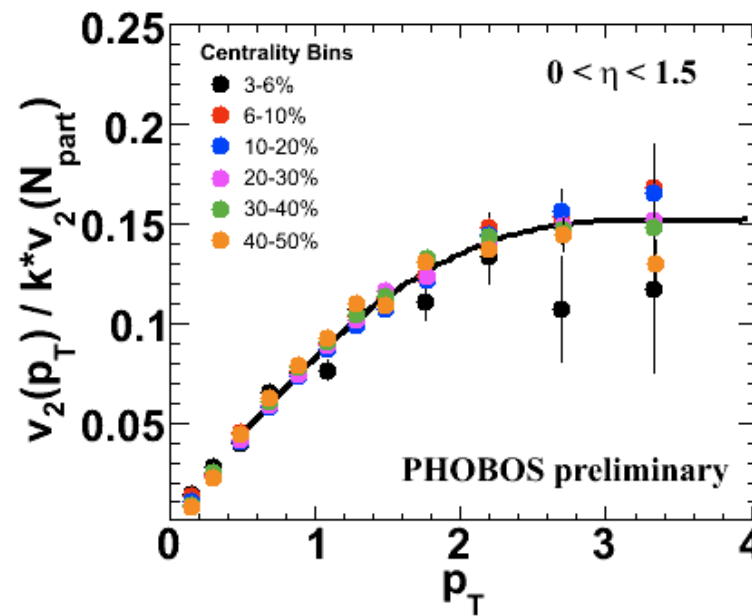
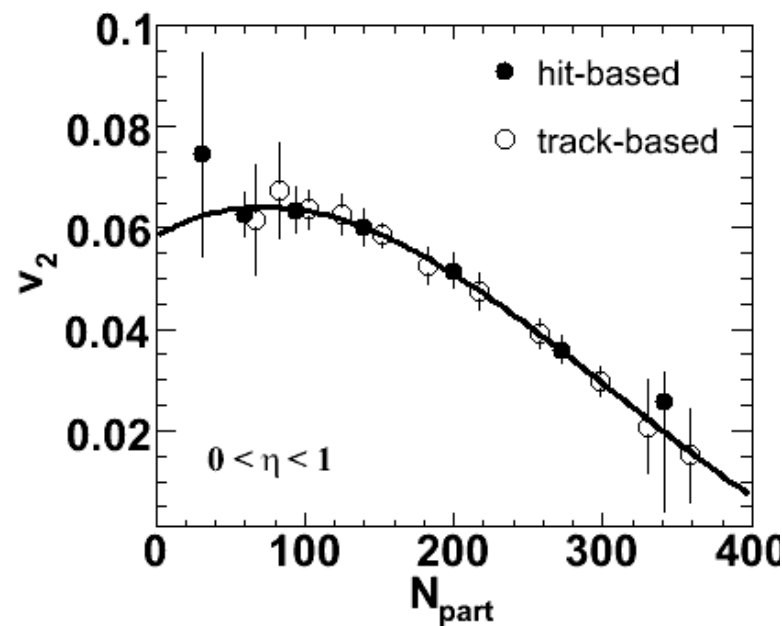
Calculating the s/b Ratio



Flow Correction

- Parameterize published PHOBOS measurements as

$$v_2(N_{\text{part}}, p_T, \eta) = A(N_{\text{part}}) B(p_T) C(\eta)$$



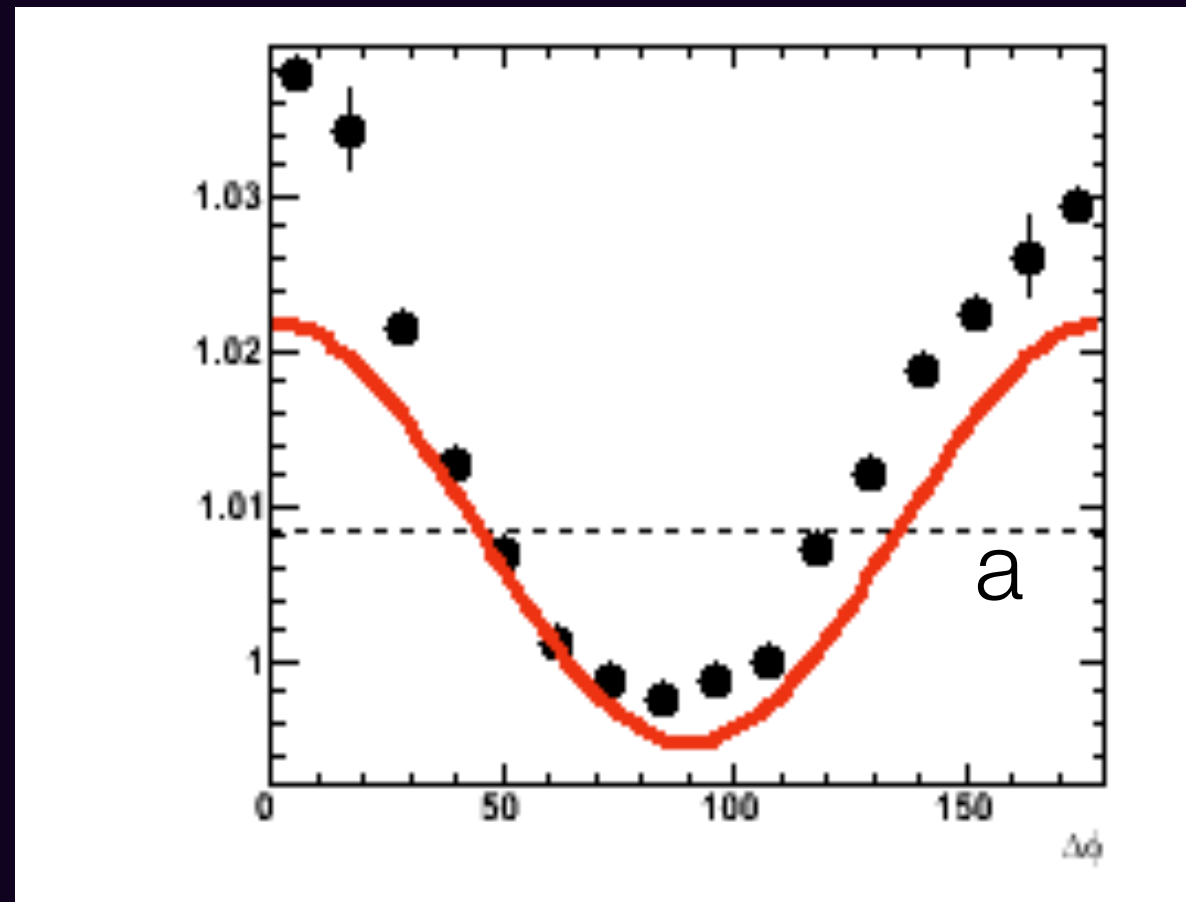
- Correct $v_2(N_{\text{part}}, \langle p_T^{\text{trig}} \rangle, \eta_{\text{trig}})$ for occupancy and
 $v_2(N_{\text{part}}, \langle p_T^{\text{assoc}} \rangle, \eta_{\text{assoc}})$ for secondaries

$$1 + 2V(\Delta\eta) \cos(2\Delta\phi)$$

$$V = \langle v_2^{\text{trig}} \rangle \langle v_2^{\text{assoc}} \rangle$$

ZYAM Normalization

$$\frac{s(\Delta\phi, \Delta\eta)}{b(\Delta\phi, \Delta\eta)} = \mathbf{a} \left[1 + 2V(\Delta\eta) \cos(2\Delta\phi) \right]$$



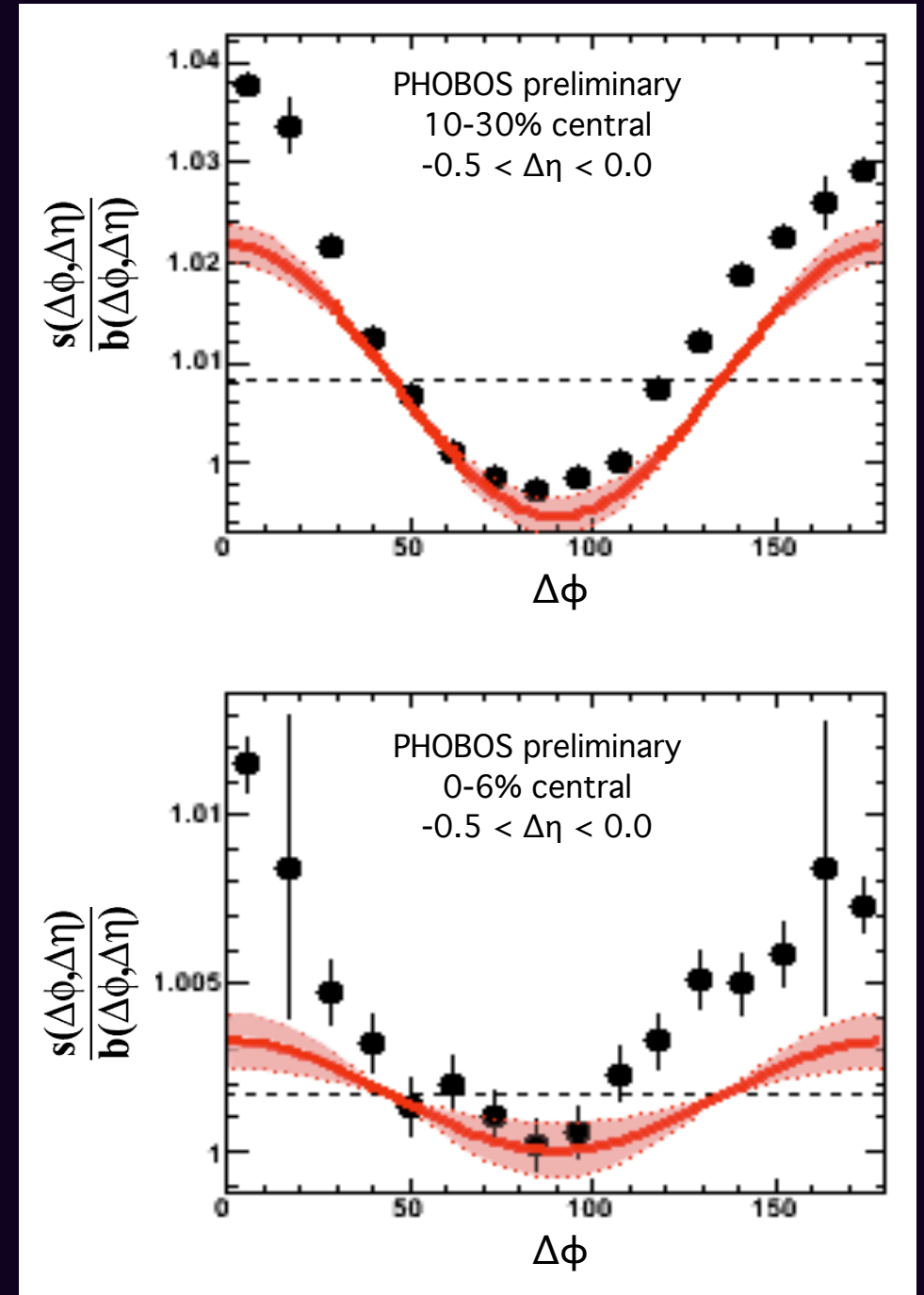
The scale factor, **a**, is calculated such that the yield after flow subtraction is zero at its minimum (ZYAM)

($a(\Delta\eta) = 1.000$ - 1.002 in central events)

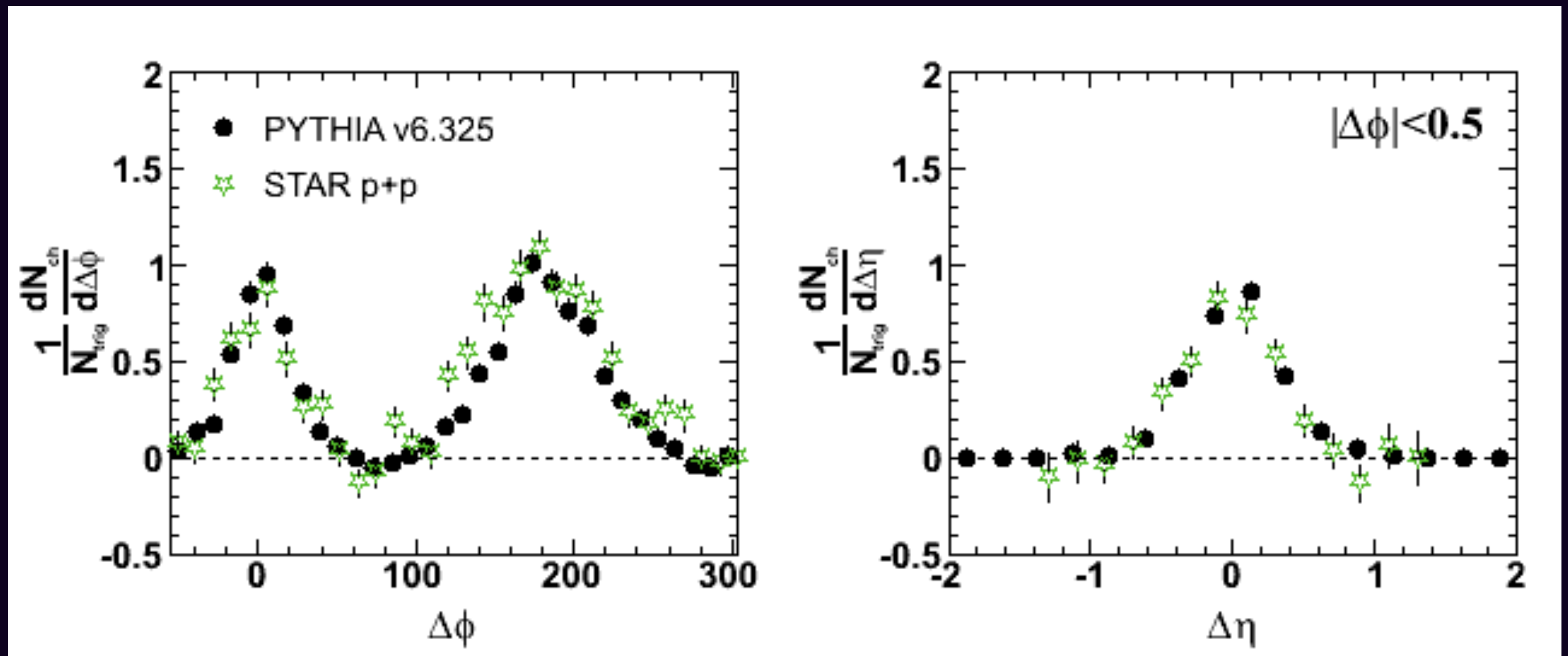
Ajitanand et al. PRC 72, 011902(R) (2005)

Systematic Errors

- The dominant systematic error in this analysis is the uncertainty on the magnitude of $\mathbf{v}_2^{\text{trig}} \mathbf{v}_2^{\text{assoc}}$
 - $\sim 14\%$ error on $\mathbf{v}_2^{\text{trig}} \mathbf{v}_2^{\text{assoc}}$ ($\eta=0$)
 - $\sim 20\%$ error on $\mathbf{v}_2^{\text{trig}} \mathbf{v}_2^{\text{assoc}}$ ($\eta=3$)
- In the most central collision -- where flow is small compared to the correlation -- the error on $\mathbf{v}_2^{\text{trig}} \mathbf{v}_2^{\text{assoc}}$ can exceed 50%.



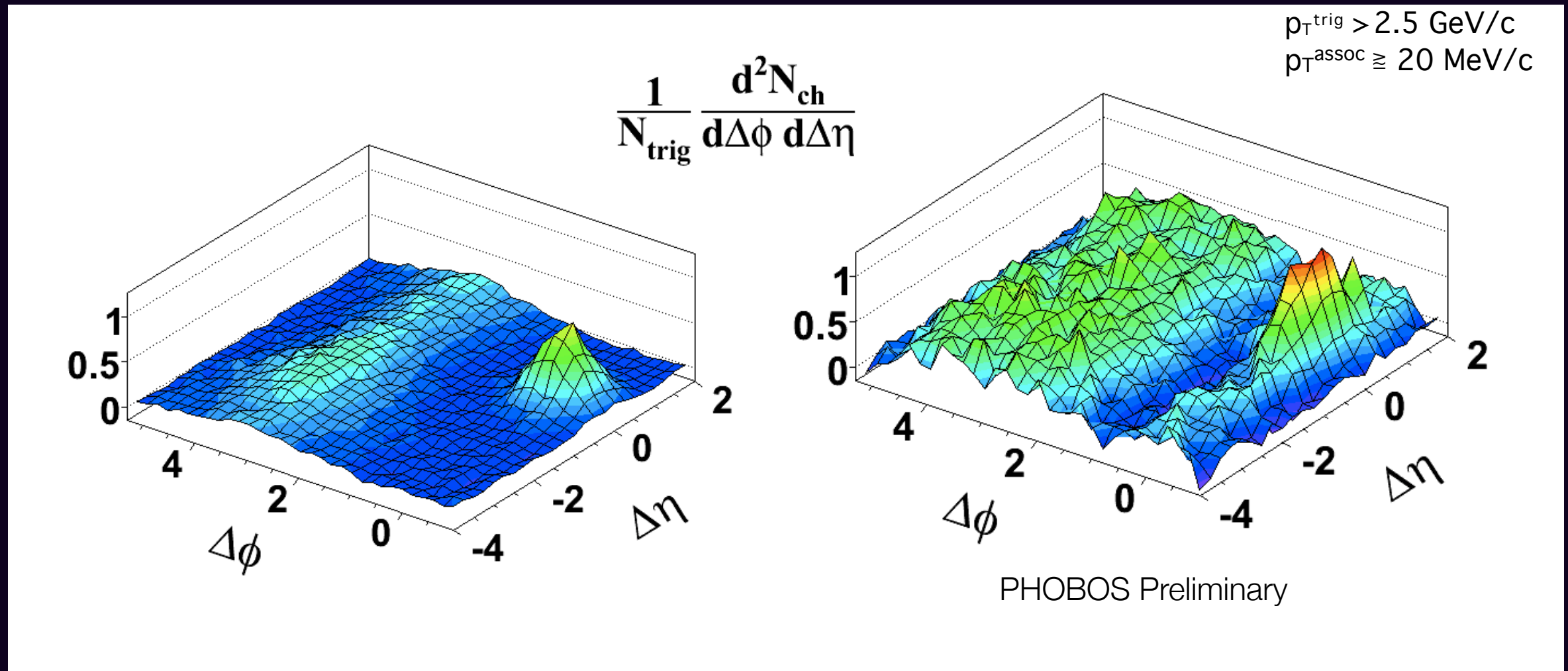
p+p reference data



PHOBOS does not have sufficient statistics for p+p

We use PYTHIA, but confirm it describes STAR data on triggered correlations

PHOBOS Data compared with p+p



PYTHIA p+p 200 GeV

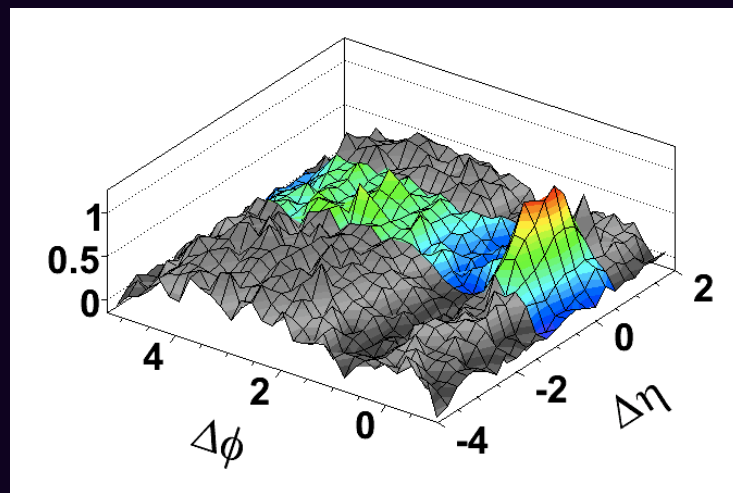
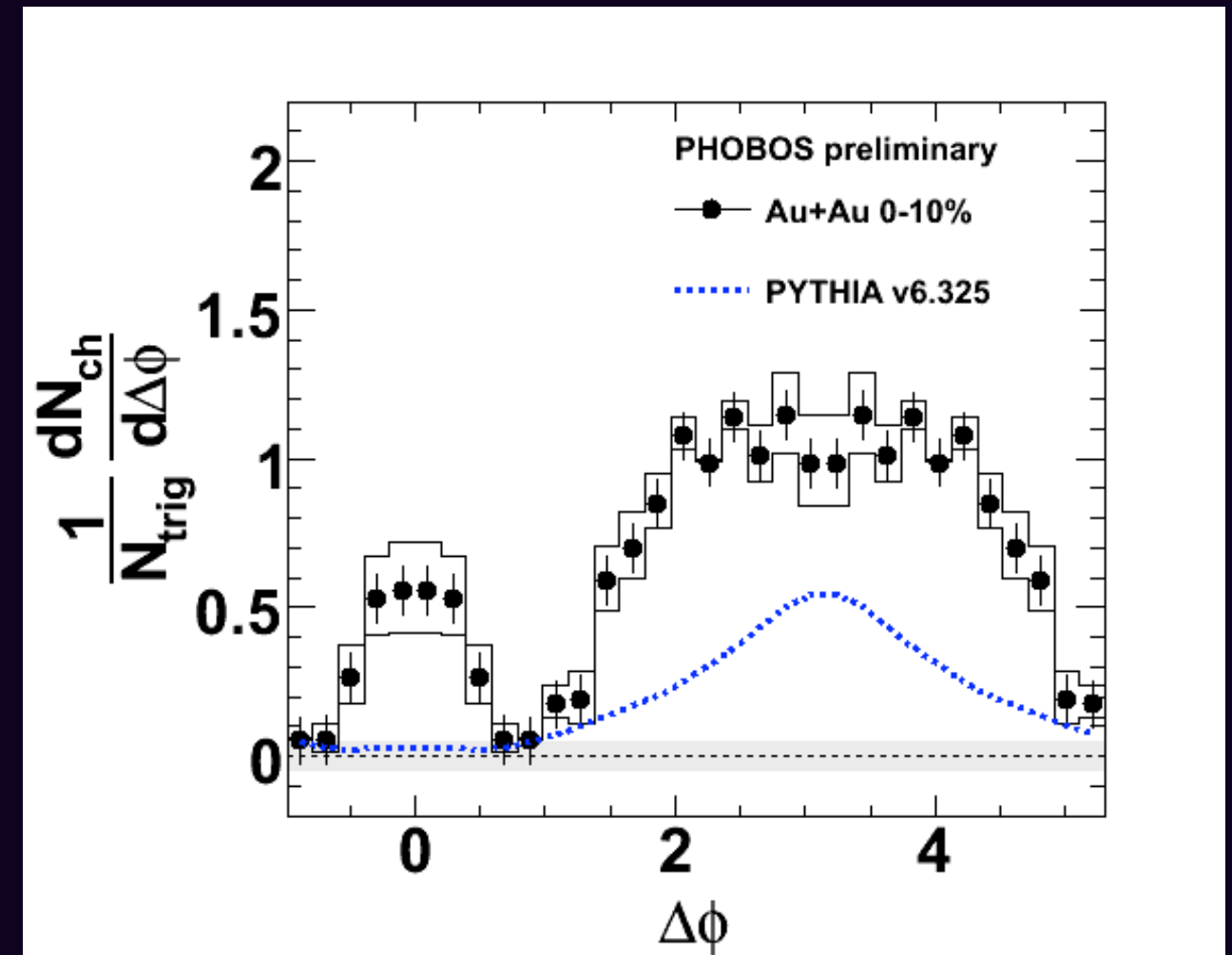
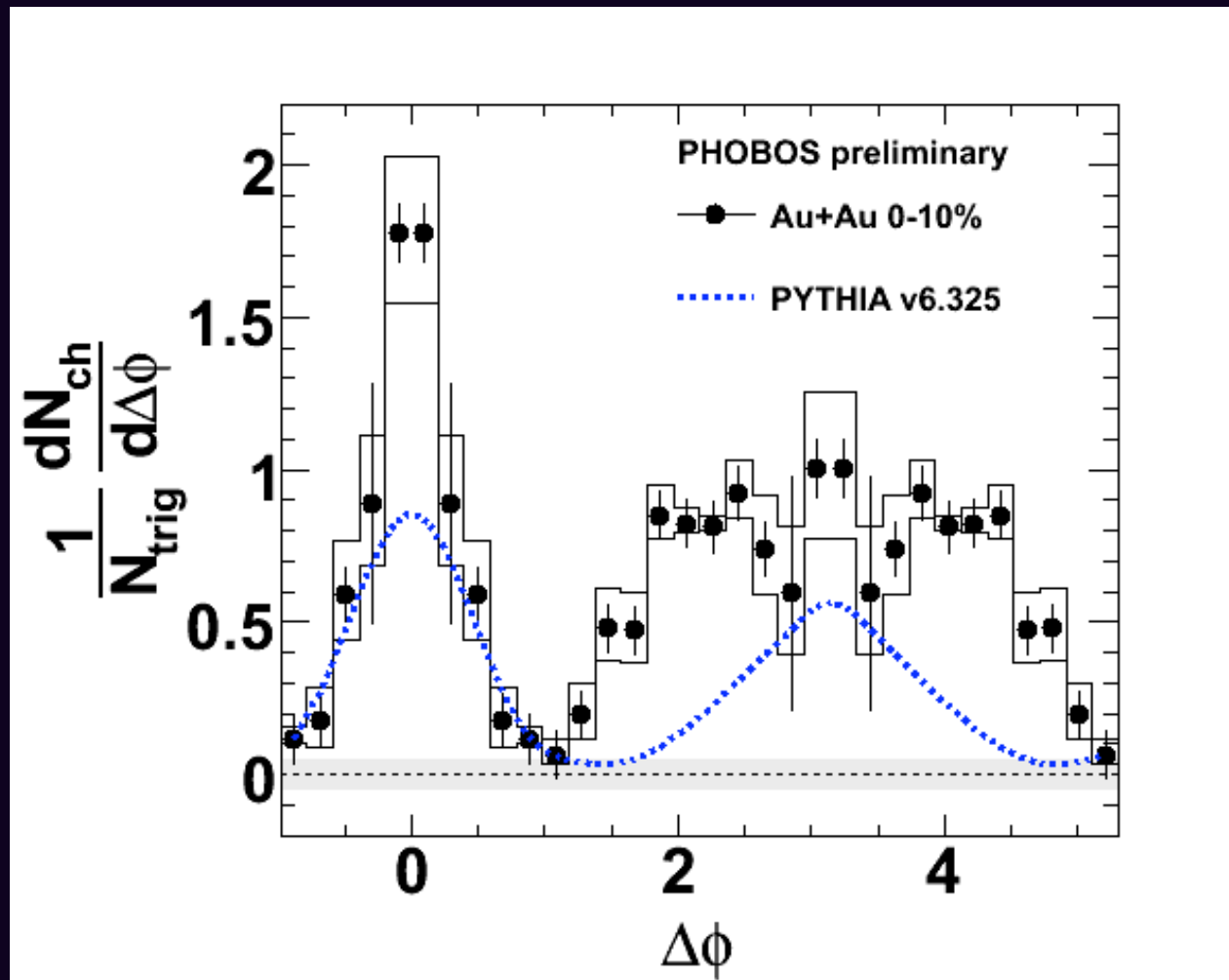
PHOBOS Au+Au 200 GeV

Large $\Delta\eta$ extent of correlations on both near and away side

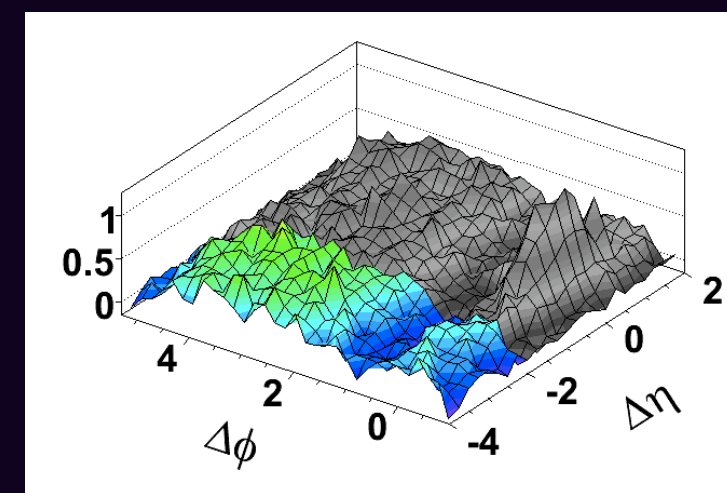
“ridge”

“Mach cone”

Slices of 2D Cond. Yield in $\Delta\eta$



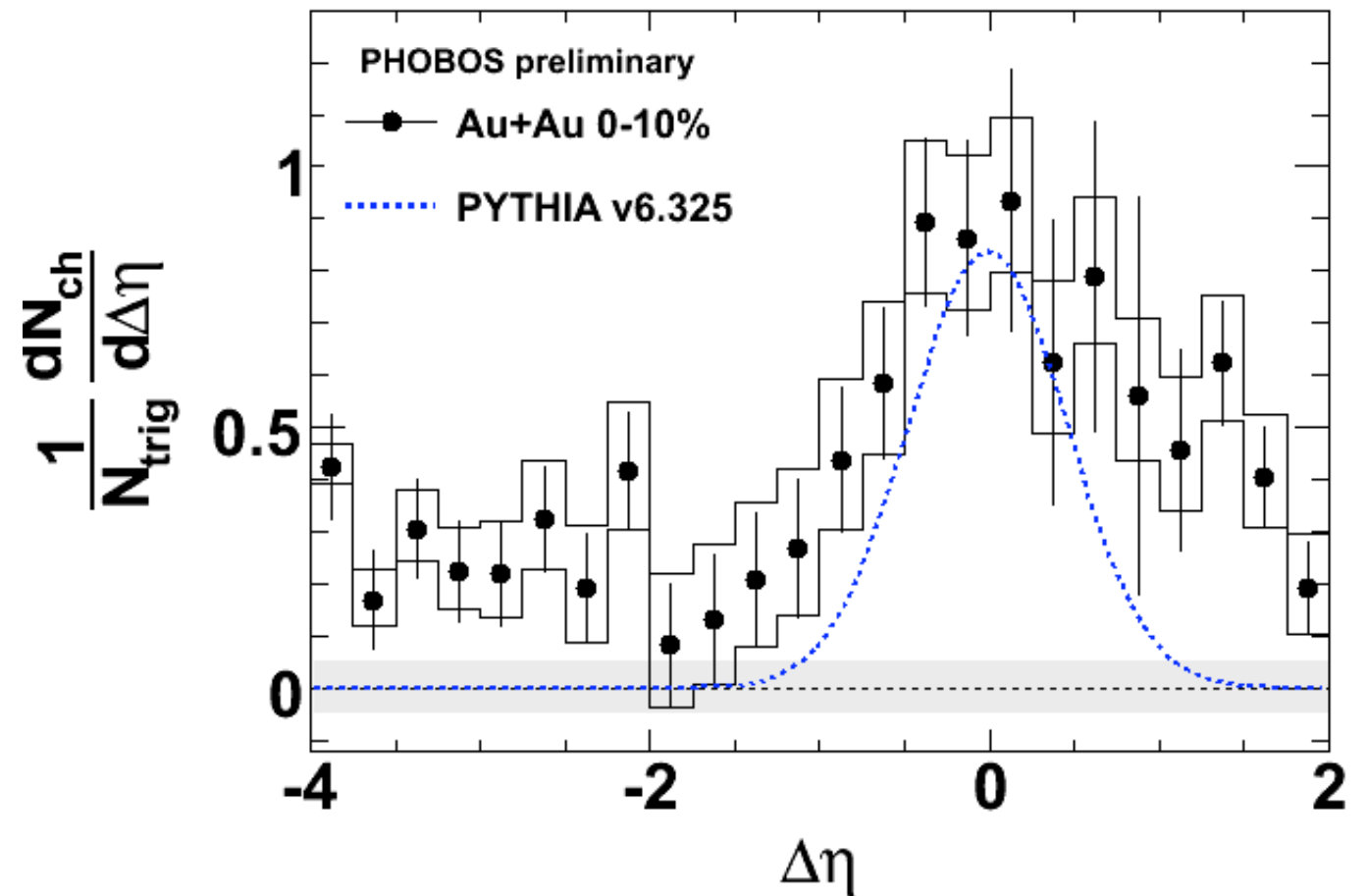
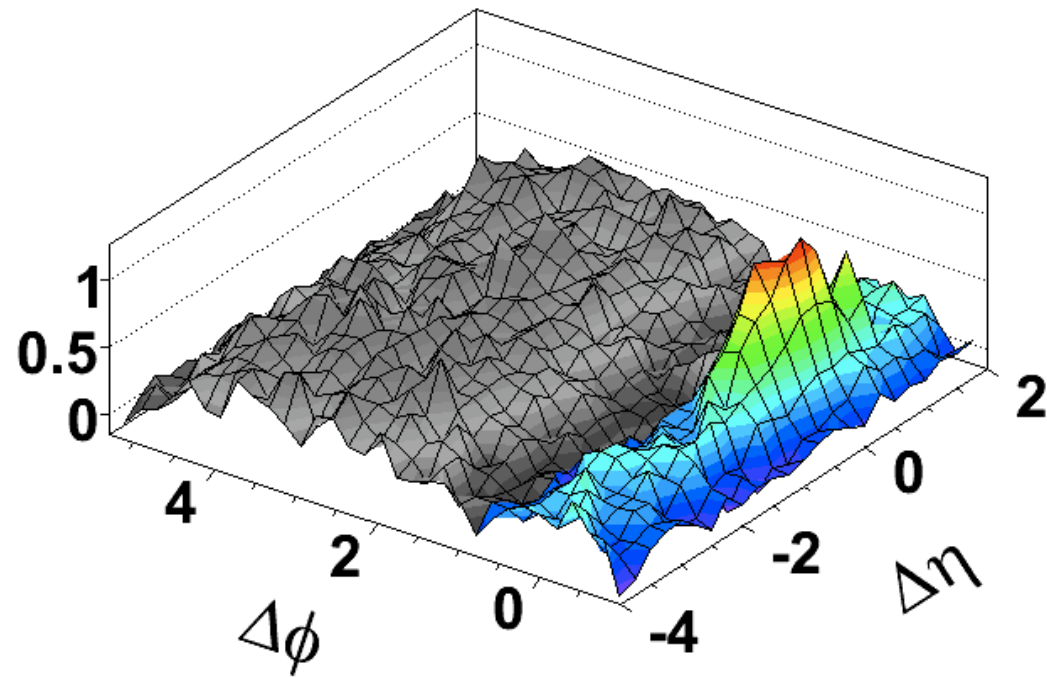
Short range
($|\Delta\eta| < 1$)



Long range
($-4 < \Delta\eta < -2$)

Nuclear modifications @ near ($|\Delta\phi| < 1$) & away, short & long range

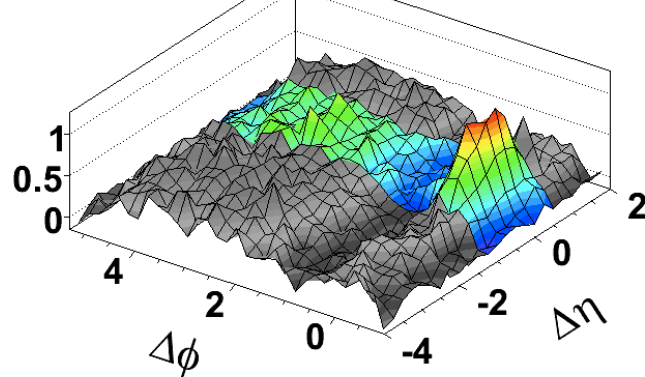
Near Side Yield vs. $\Delta\eta$



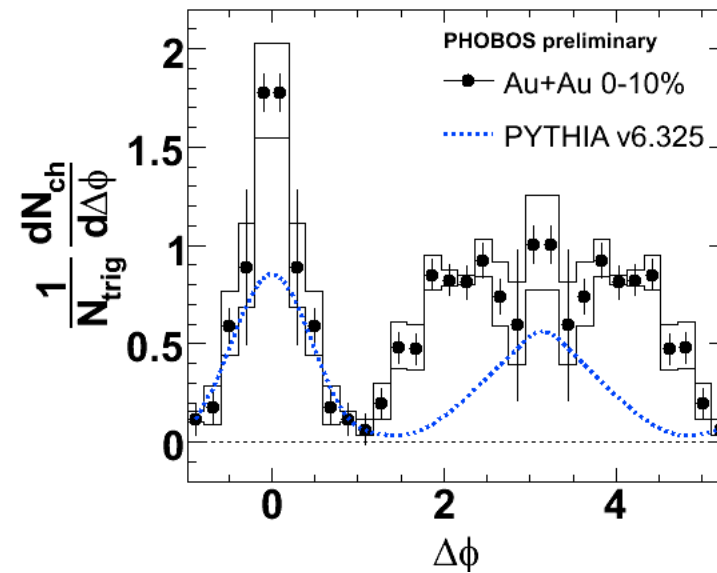
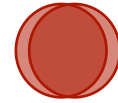
Integrating over near side, find that the correlated yield does not go to zero at large $\Delta\eta \rightarrow$ ridge appears to be “long-range”

Yield vs. Centrality and $\Delta\eta$

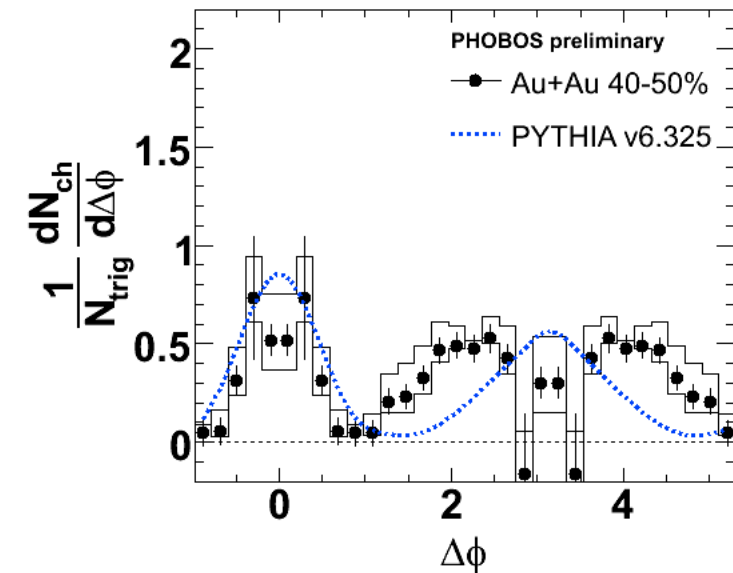
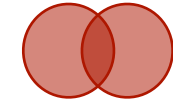
Short-range $|\Delta\eta| < 1$



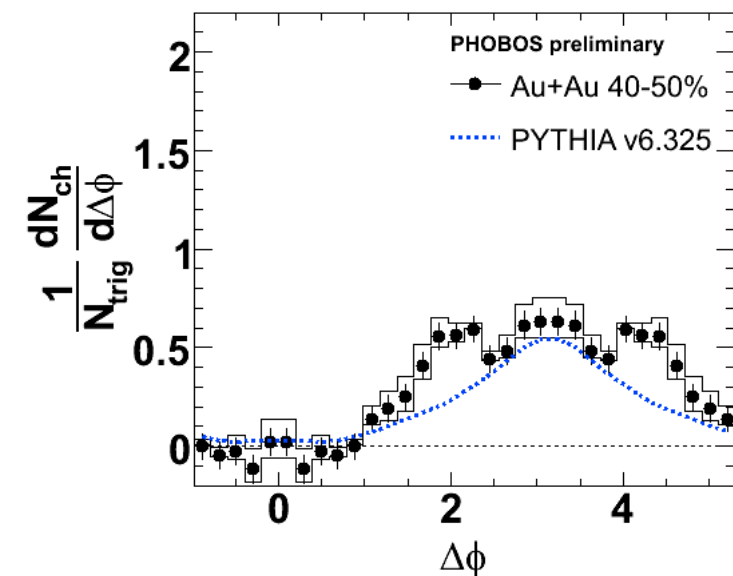
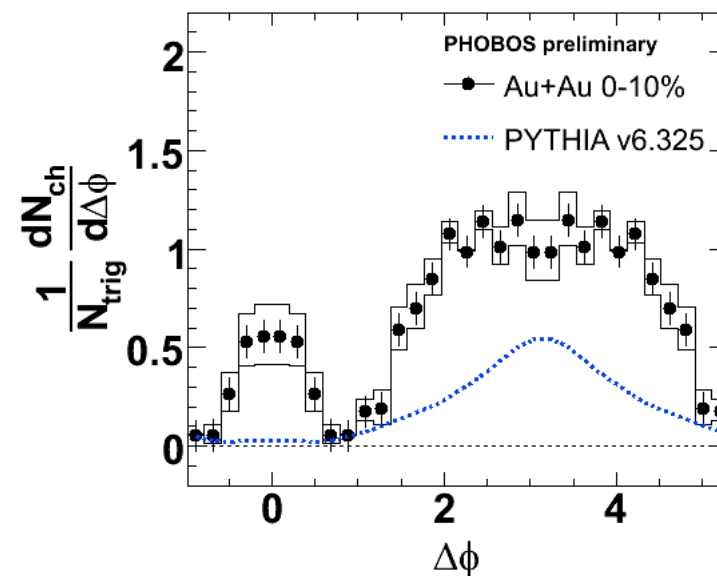
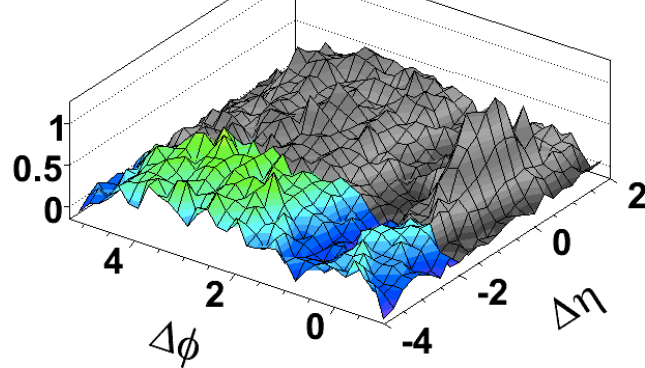
0-10%



40-50%



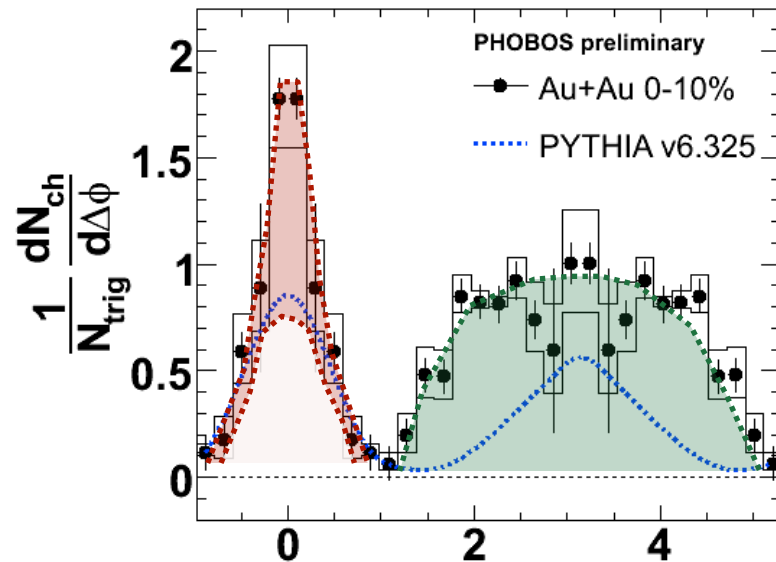
Long-range $-4 < \Delta\eta < -2$



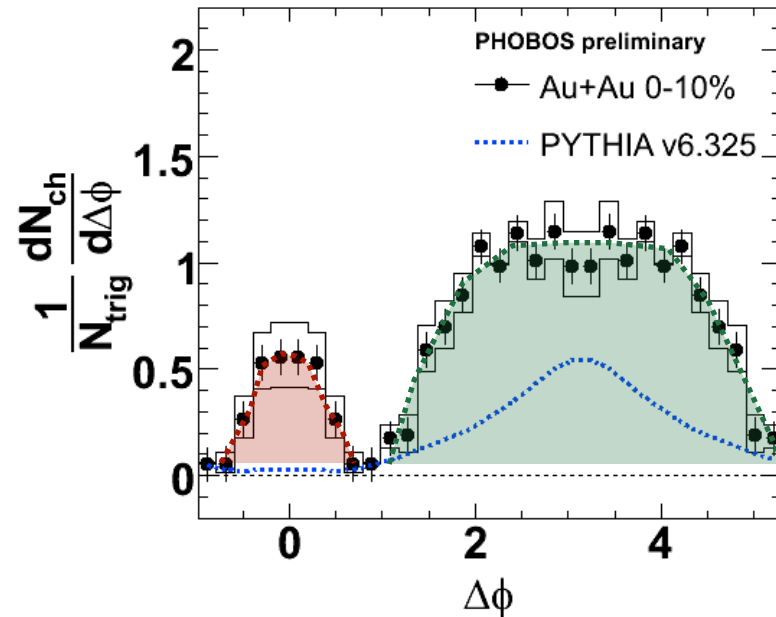
Away side decreases slightly, but ridge disappears

Associated yield vs. Centrality

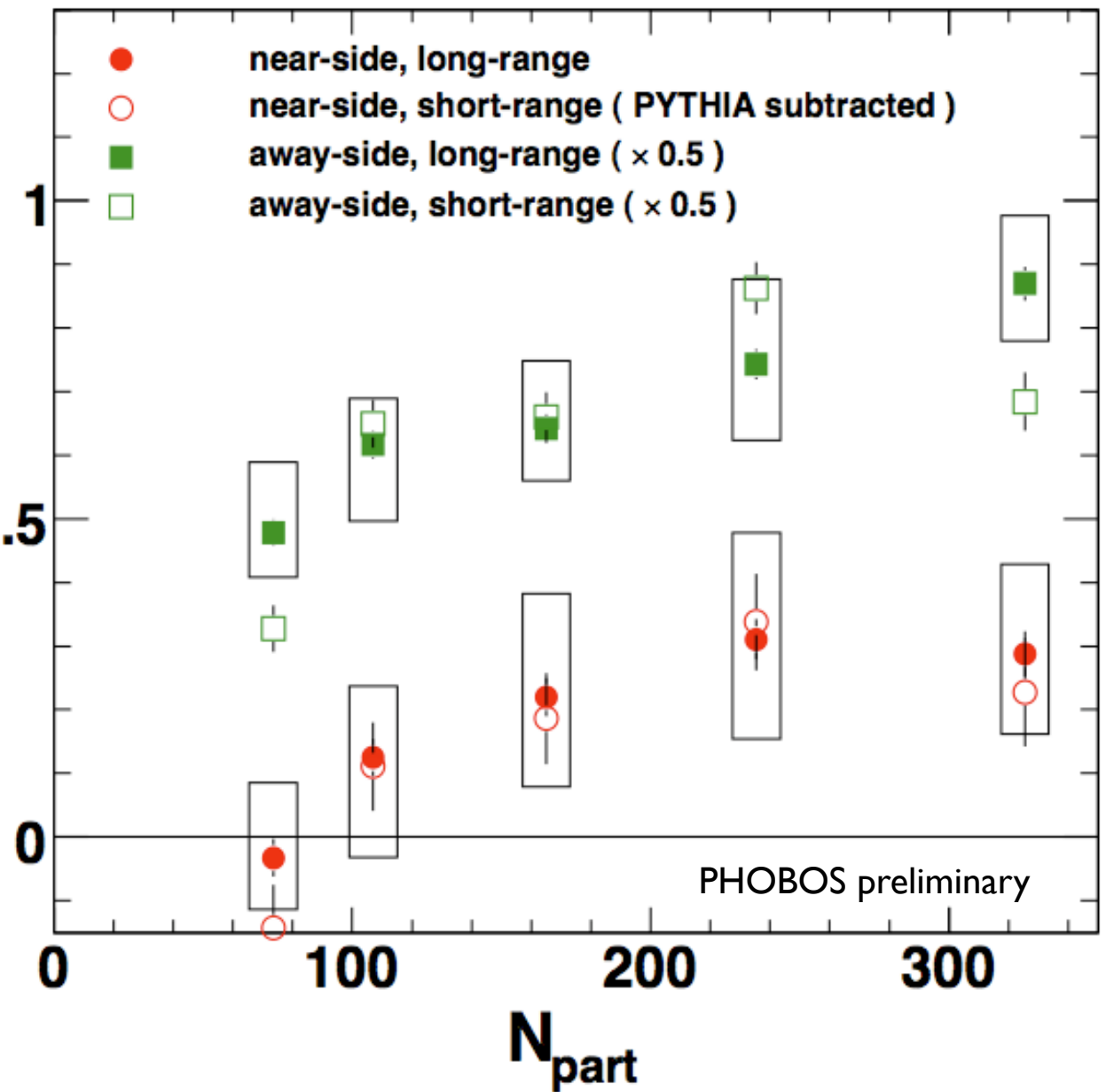
Short-range $|\Delta\eta| < 1$



Long-range $-4 < \Delta\eta < -2$

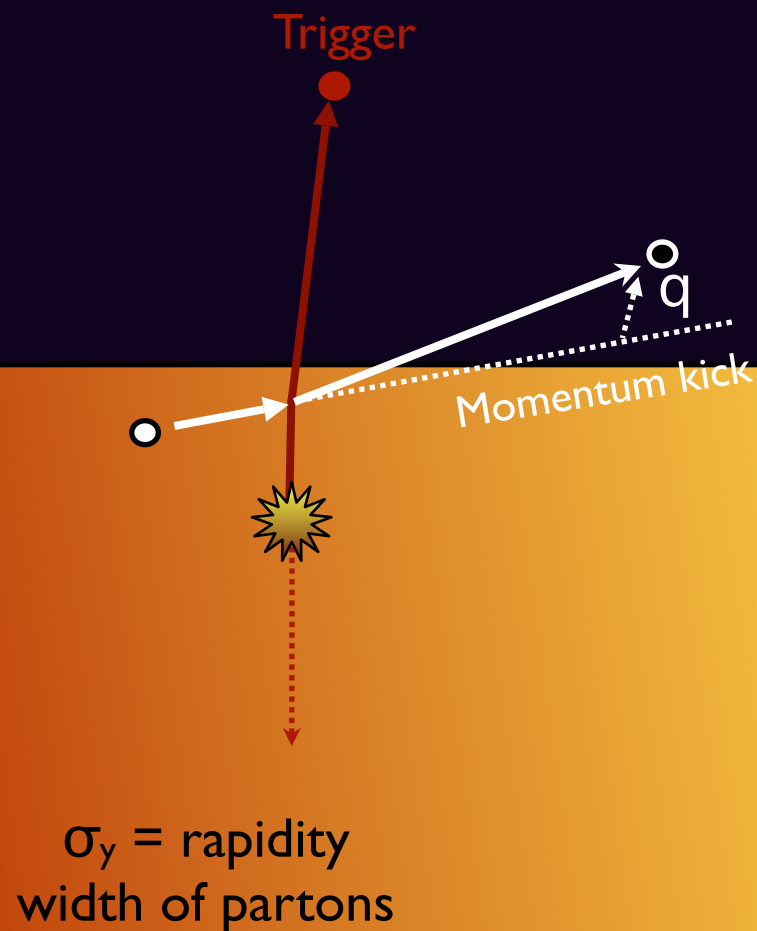


$$\left\langle \frac{1}{N_{\text{trig}}} \frac{dN_{\text{ch}}}{d\Delta\eta} \right\rangle$$

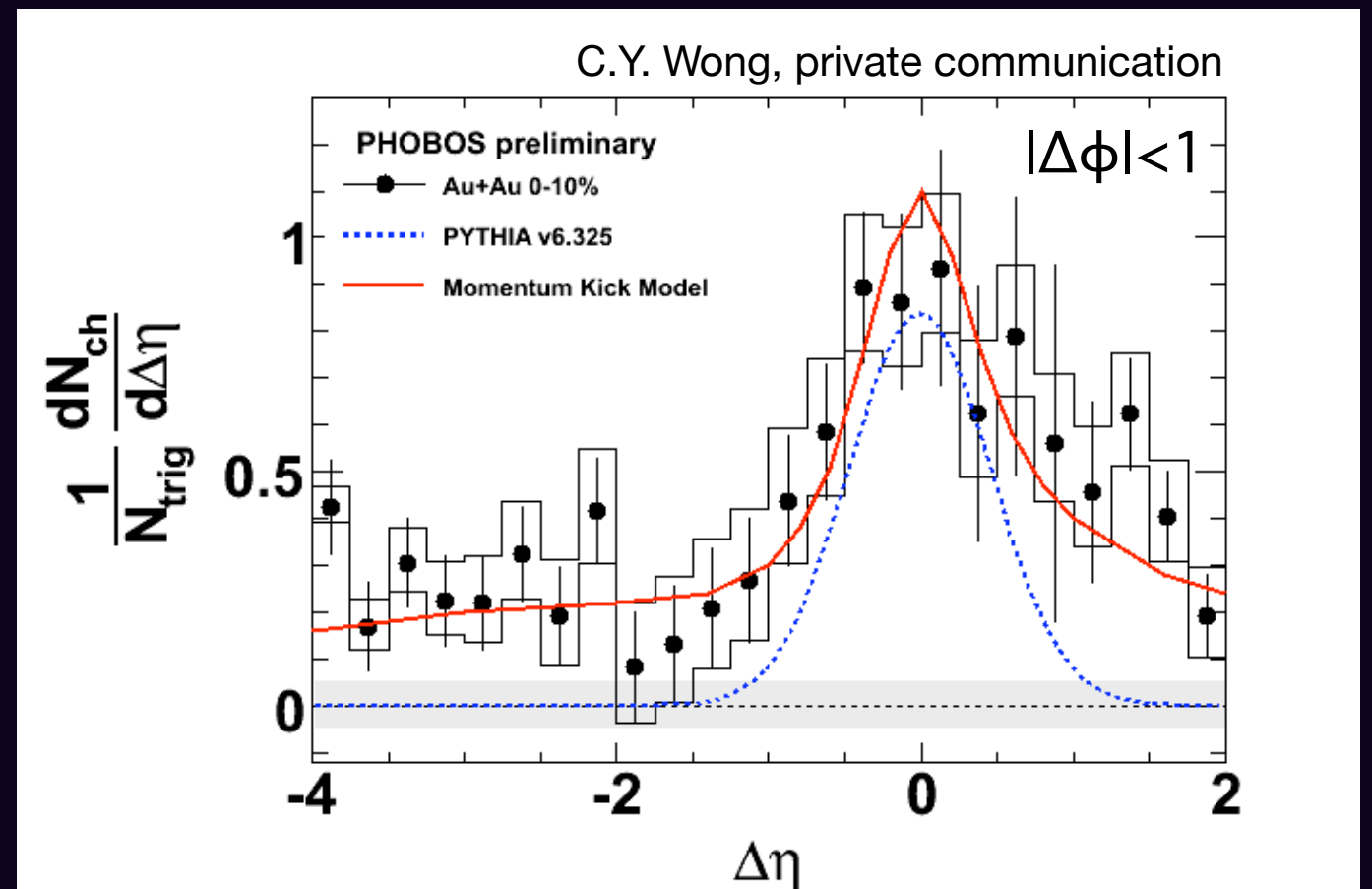


Based on PYTHIA subtraction (at short range only),
 observe that ridge & “Mach cone” yield is the same at short and long range

One Model Comparison



C.Y. Wong, PRC **76**, 054908 (2007)



Wong's momentum kick model suggests ridge comes from collision of jet with bulk in early stage

Conclusions: Triggered Correlations

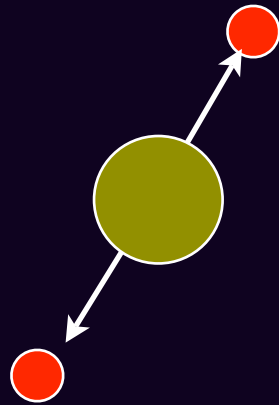
- **PHOBOS is able to contribute to this discussion by measuring inclusive correlated yield at large $\Delta\eta$**
- **Results shown for 0-50% centrality in 200 GeV Au+Au collisions**
- **“Ridge” yield extends out to $\Delta\eta=4$, essentially constant after subtracting jet contribution**
 - Disappears at $N_{\text{part}} \sim 80$
- **Long range of the ridge is a non-trivial feature, since it requires large momentum transfers, or very short times**

Inclusive Correlations

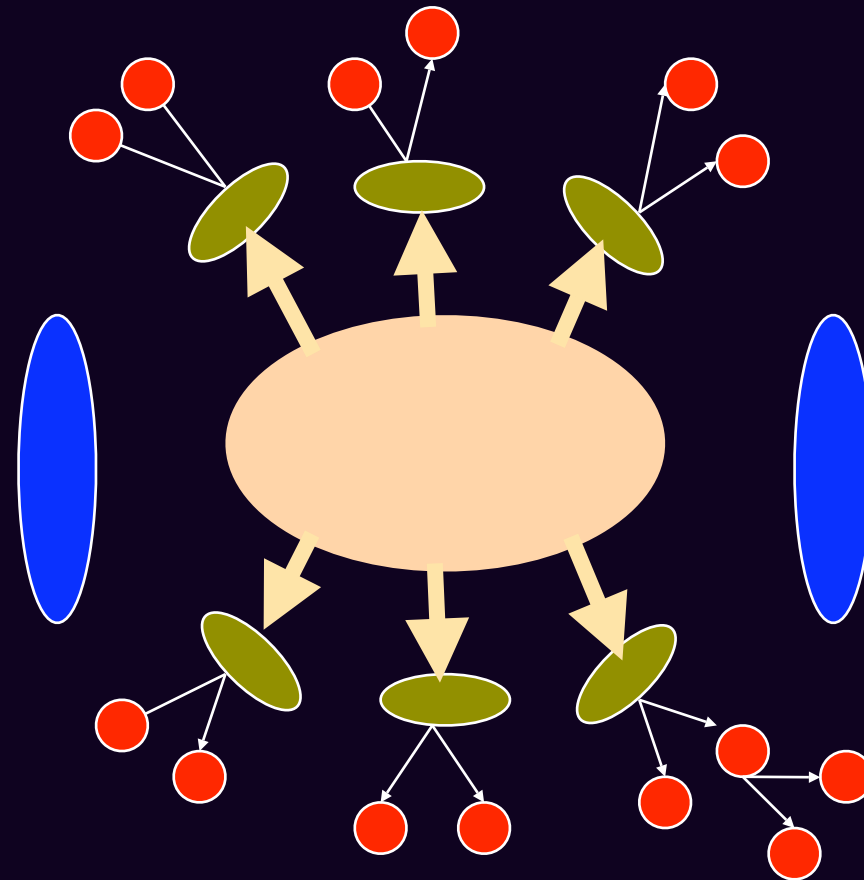
Inclusive Two-Particle Correlations

- **What about correlations not associated with a high p_T trigger particle?**
- **Jets are not the only source of correlated particle production**
- **“Cluster hadronization” has been discussed for many years now, given the observation of strong 2-particle correlations in p+p collisions at all energies**

Cluster Hadronization Scenario



Hadronization proceeds via “clusters”, which decay isotropically in their rest frame



Multiparticle production: many clusters, which decay into hadrons (which themselves decay!)

Aside: Short vs. Long Range

from the mixing of components (events with different multiplicities n), C_L . The inclusive correlation function is related to the semi-inclusive function C_n at fixed charged multiplicity n as [10]:

$$C(\eta_1, \eta_2) = C_S(\eta_1, \eta_2) + C_L(\eta_1, \eta_2), \quad (2.7)$$

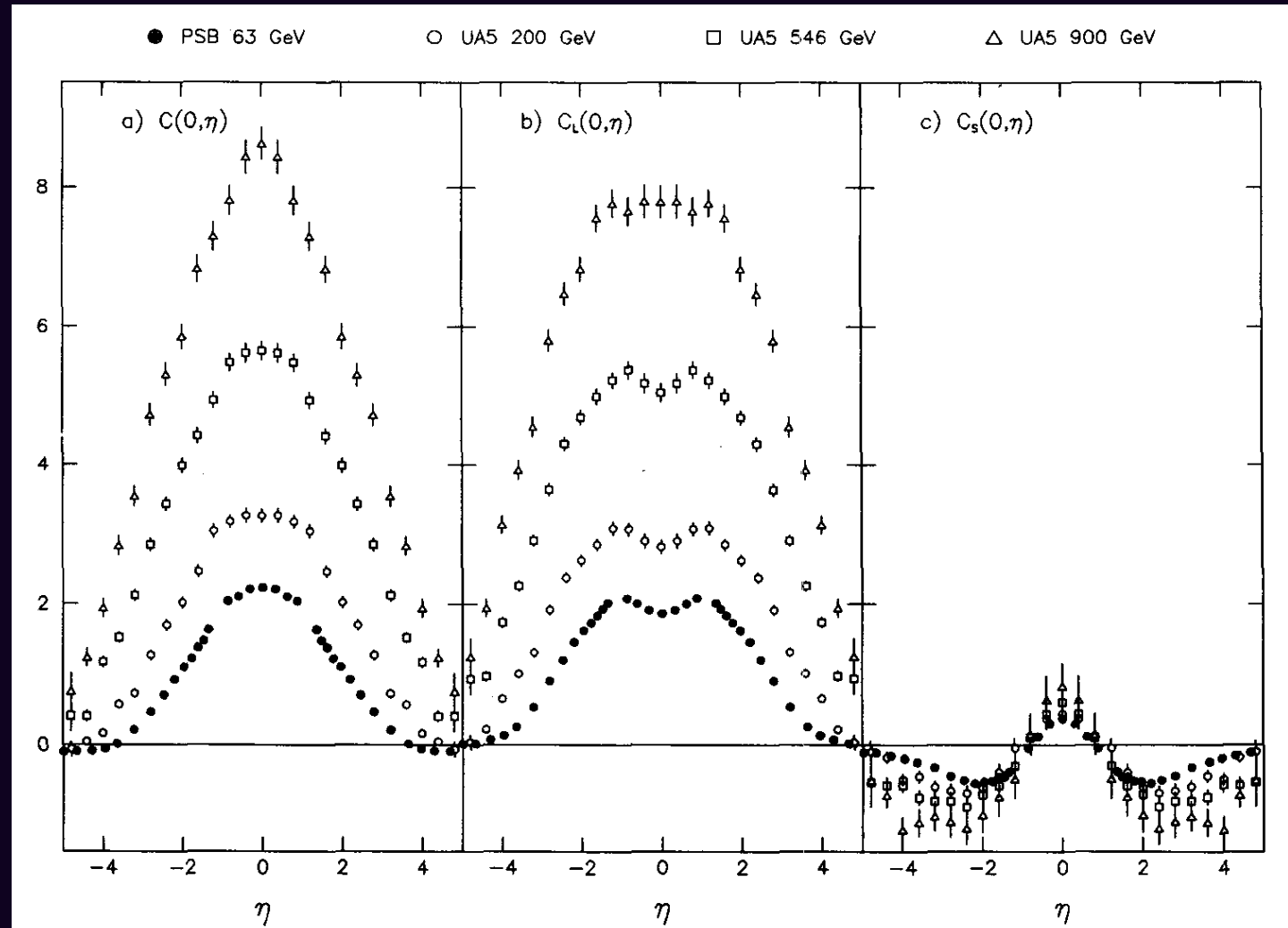
where

$$C_S(\eta_1, \eta_2) = \sum_n \frac{\sigma_n}{\sigma} C_n(\eta_1, \eta_2) \quad (2.8)$$

and

$$C_L(\eta_1, \eta_2) = \sum_n \frac{\sigma_n}{\sigma} (\rho^I(\eta_1) - \rho_n^I(\eta_1))(\rho^I(\eta_2) - \rho_n^I(\eta_2)). \quad (2.9)$$

Figure 1b shows the contribution of $C_L(\eta_1, \eta_2)$ and Fig. 1c the contribution of $C_S(\eta_1, \eta_2)$ to the inclusive correlation function.



Long range: mixing events w/ different multiplicities

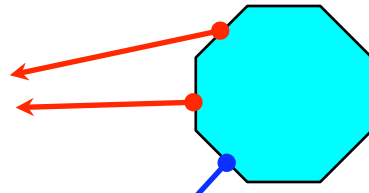
Short range: average over two-particle correlation @ fixed n

**Long range correlations have been in the literature for years,
but short range correlations ~constant w/ energy**

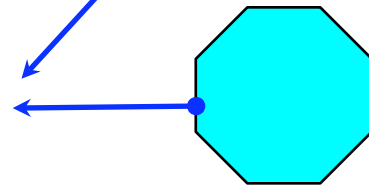
Constructing Correlation Function

$$R(\Delta\eta, \Delta\phi) = \langle (n-1) \left(\frac{F_n(\Delta\eta, \Delta\phi)}{B_n(\Delta\eta, \Delta\phi)} - 1 \right) \rangle$$

Foreground: $F_n(\Delta\eta, \Delta\phi)$
(correlated + uncorrelated pairs):



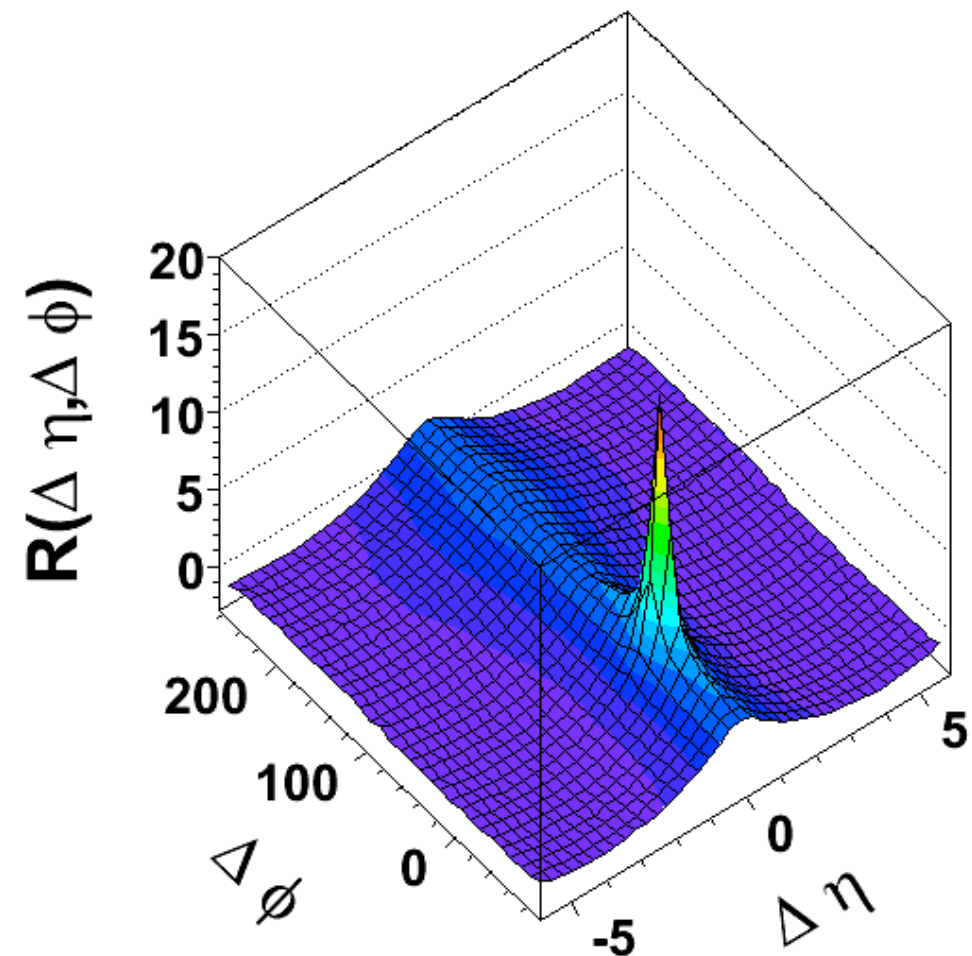
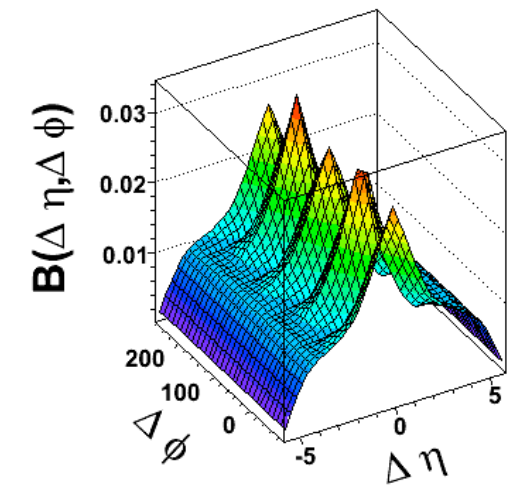
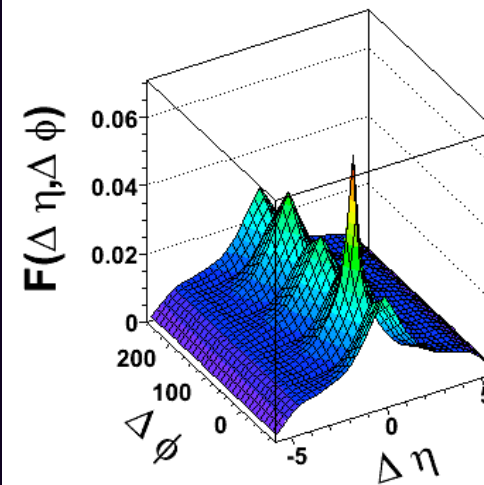
Background: $B_n(\Delta\eta, \Delta\phi)$
(uncorrelated pairs):



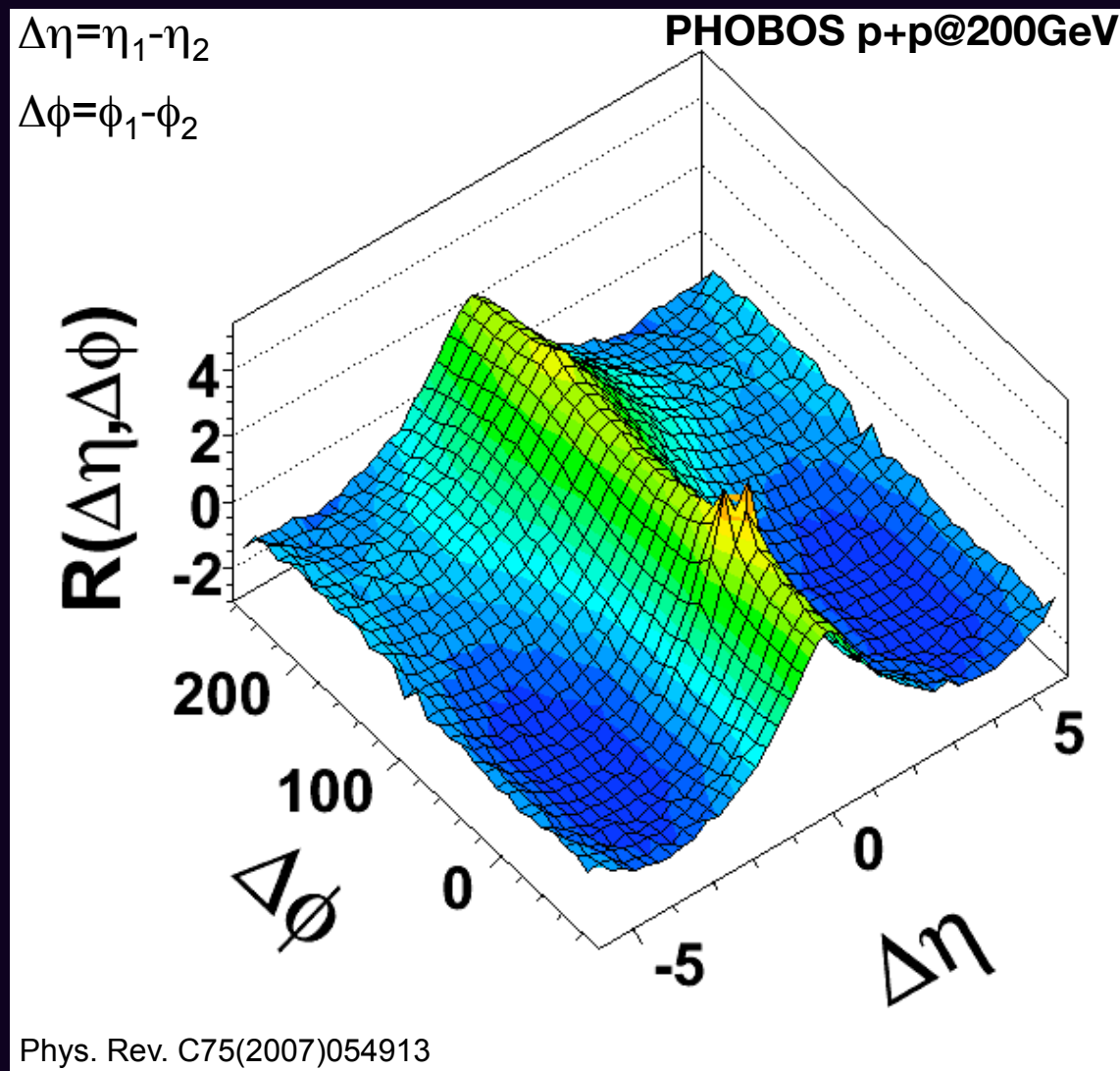
(n-1) weighting makes
CF multiplicity independent

Peak at $\Delta\phi, \Delta\eta=0$ dominated by delta
rays and conversions
(this bin always removed)

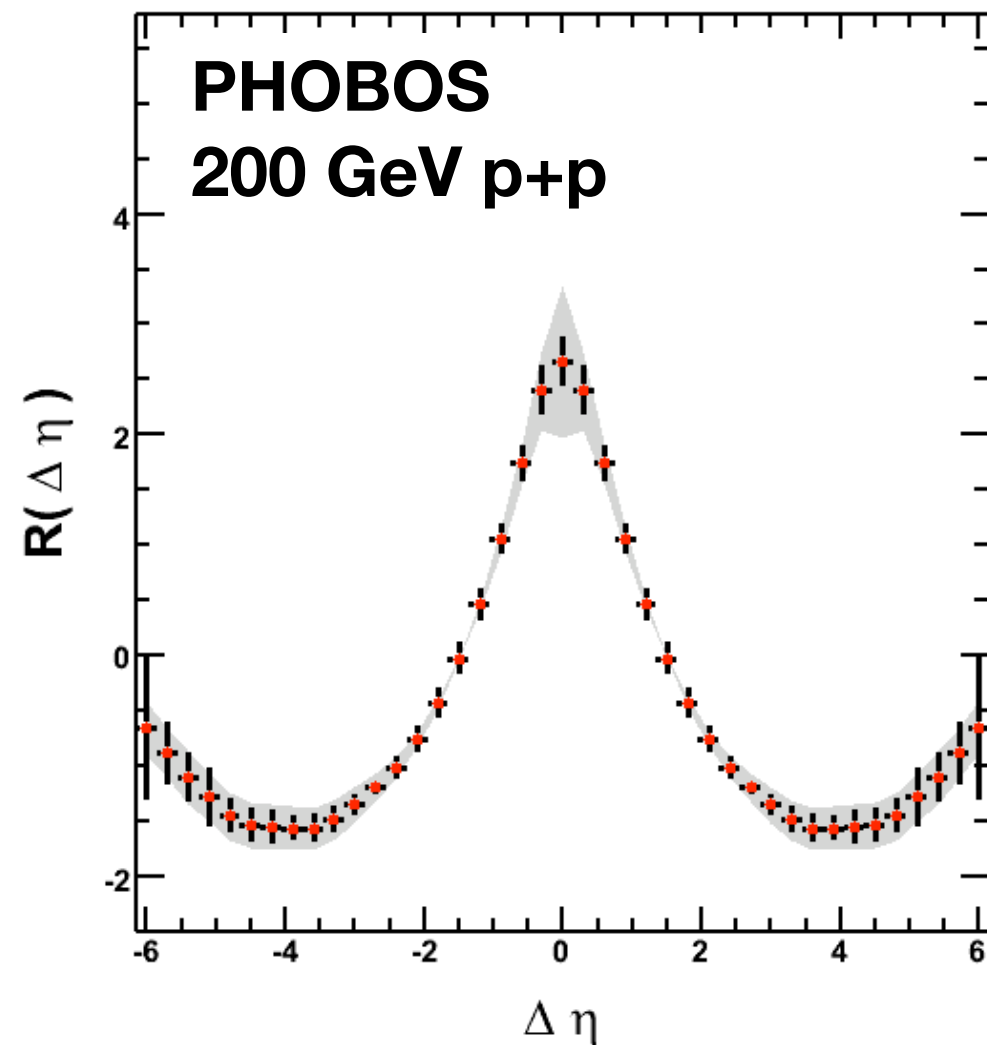
MC-based corrections for
secondaries & acceptance gaps



First tried on RHIC p+p data



2D correlation function



Integrated over $\Delta\phi$
(first F, then B \rightarrow R)

Cluster Model Fit

Effective cluster width δ
related to correlation width:
Gaussian shape is assumed

$$\Gamma(\Delta\eta) \propto \exp\left(-\frac{(\Delta\eta)^2}{4\delta^2}\right)$$

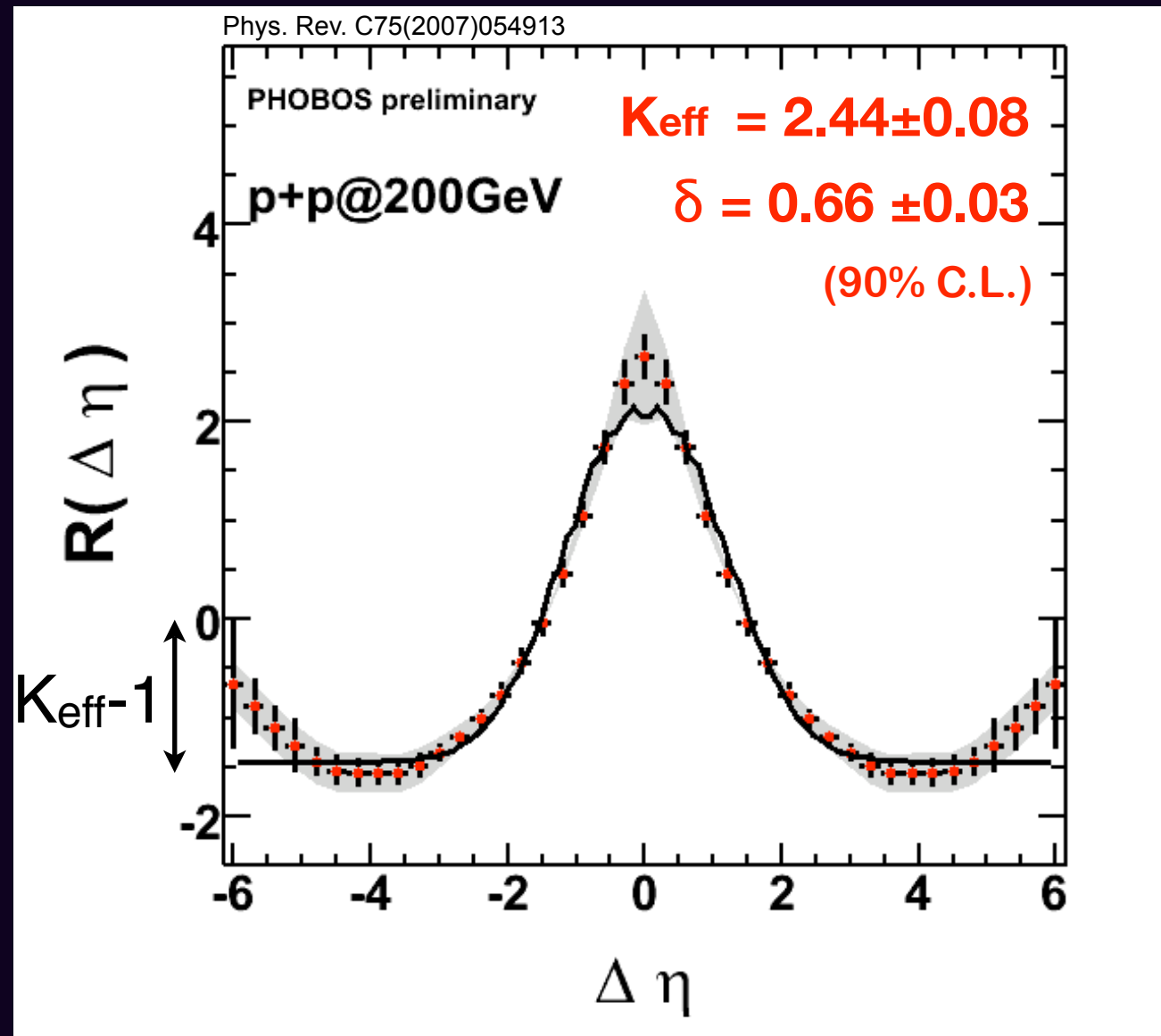
$\delta=0.7$ for isotropic decay

$$R(\Delta\eta) = \alpha \left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1 \right]$$

Effective cluster size K_{eff}
related to correlation strength:
convolution of mean & sigma
of multiplicity distribution per cluster

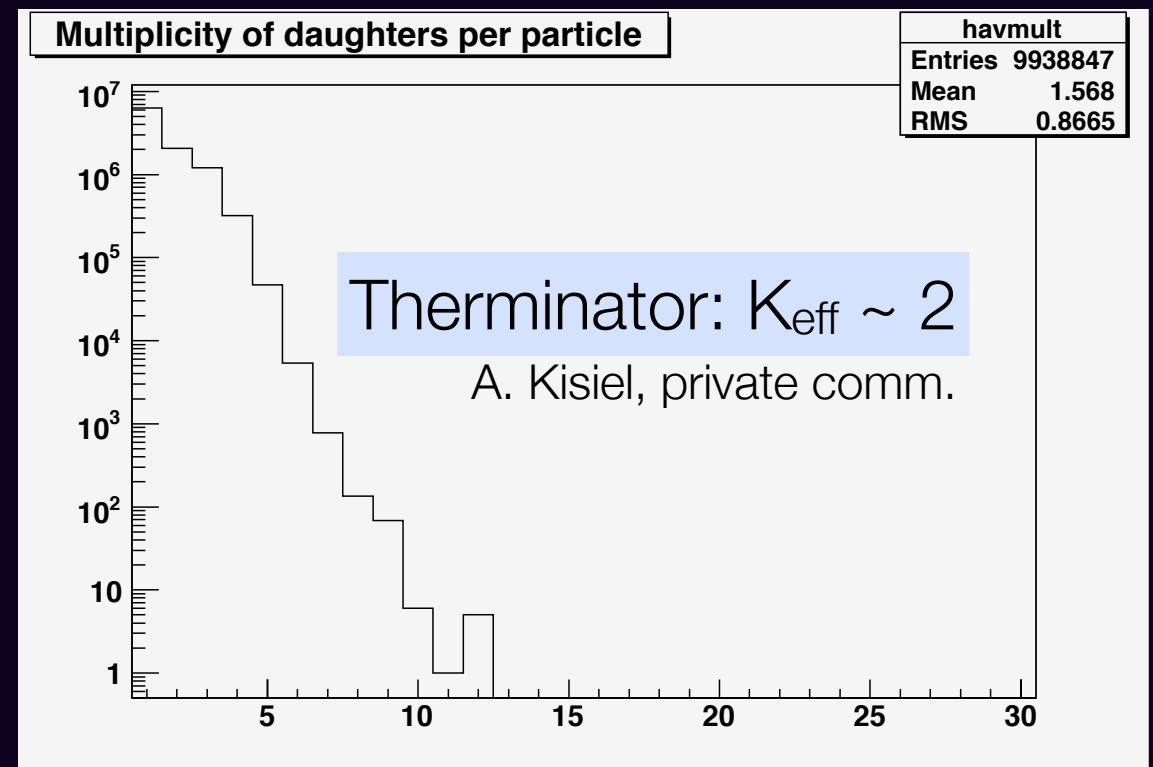
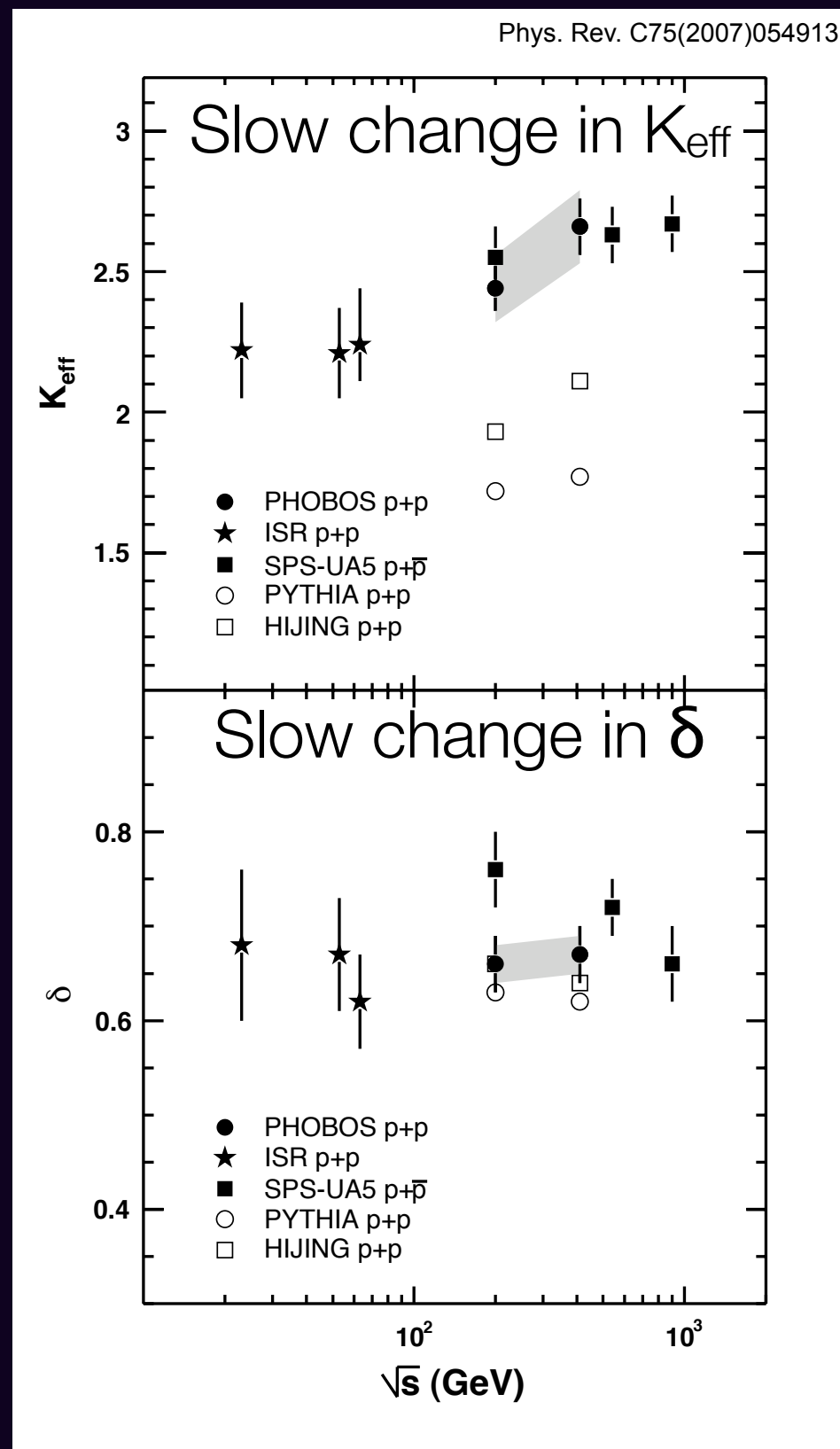
$$K_{\text{eff}} = \alpha + 1 = \frac{\langle k(k-1) \rangle}{\langle k \rangle} + 1 = \langle k \rangle + \frac{\sigma_k^2}{\langle k \rangle}$$

Short Range Correlations in p+p



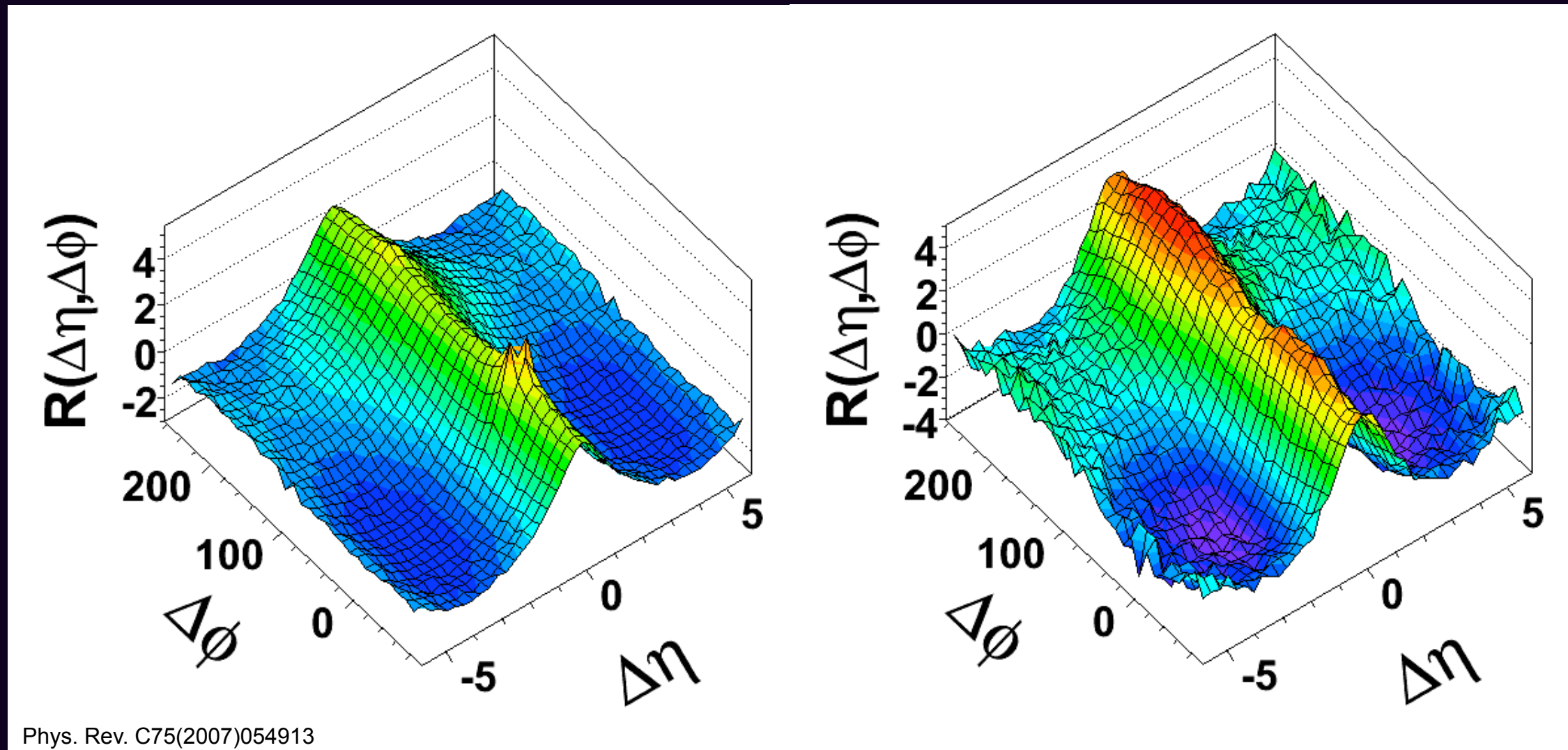
We observe ~ 1.5 additional particles correlated with every charged particle over ± 3 units in η

Energy Systematics in $p+p$



Data suggests much higher cluster size than MCs, which are themselves consistent with clusters as just resonance decays (cf. Therminator)

2D Comparison with Cluster Model



Cluster model (an example given here, not fit to data)
does not just give a 1D shape,
but helps understand features of 2D CF

Can resonances make a near side peak?

Nuclear Physics B86 (1975) 201–215 North-Holland Publishing Company

ANGULAR CORRELATIONS BETWEEN THE CHARGED PARTICLES PRODUCED IN pp COLLISIONS AT ISR ENERGIES

K EGGERT, H FRENZEL and W THOMÉ
III Physikalisches Institut der Technischen Hochschule, Aachen, Germany

B BETEV *, P DARRIULAT, P DITTMANN,
M HOLDER, K T McDONALD, T MODIS and H G. PUGH **
CERN, Geneva, Switzerland

K TITTEL
Institut für Hochenergiephysik, Heidelberg, Germany

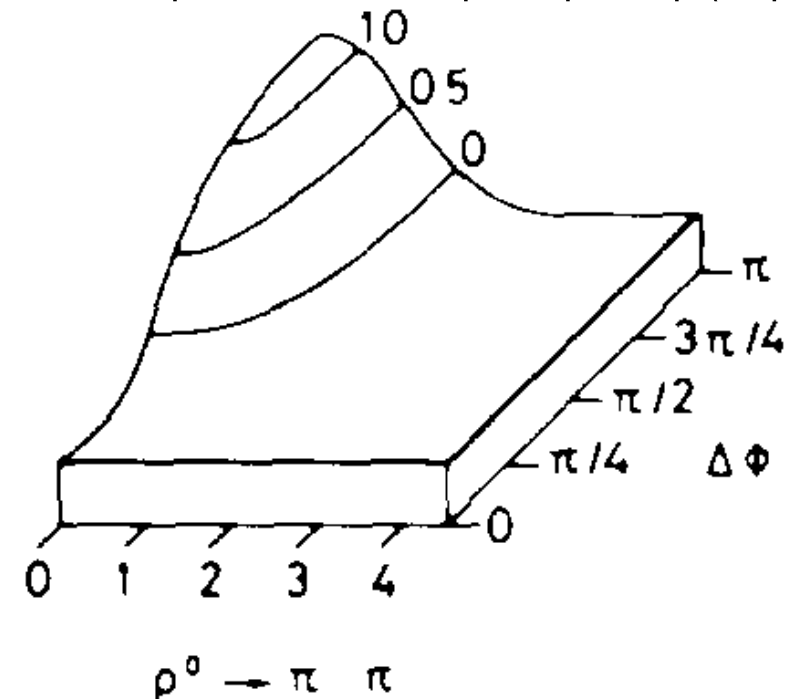
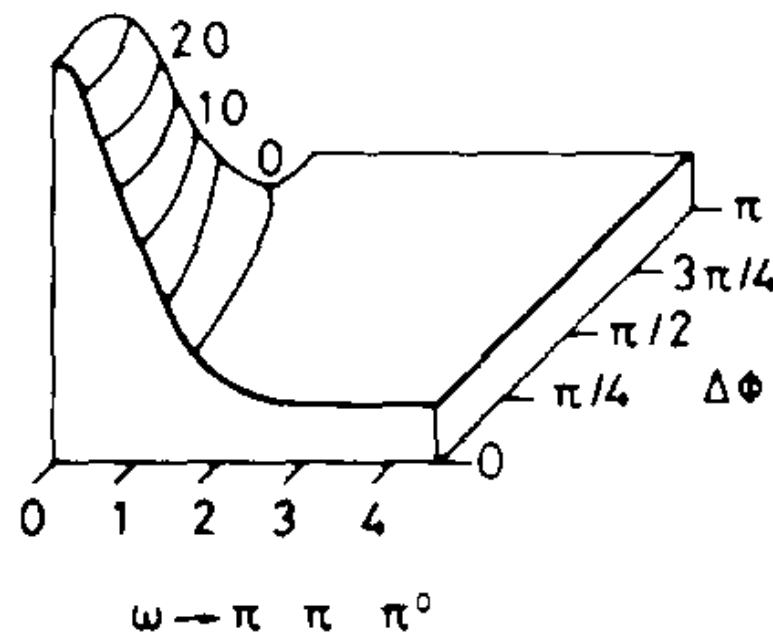
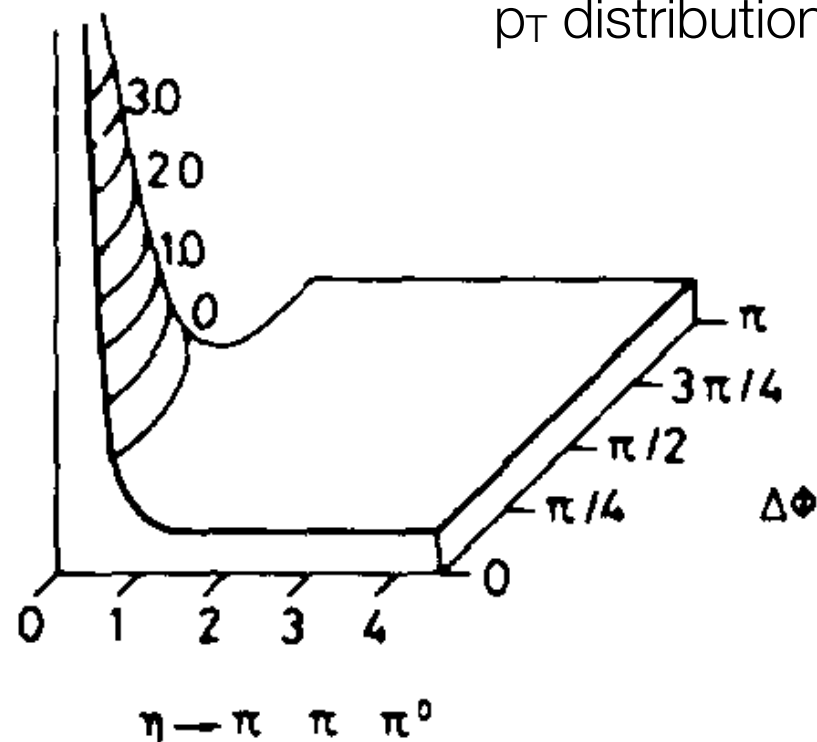
I. DERADO, V ECKARDT, H J GEBAUER,
R MEINKE, O R SANDER *** and P SEYBOTH
Max-Planck-Institut für Physik und Astrophysik, Munich, Germany

Received 11 November 1974

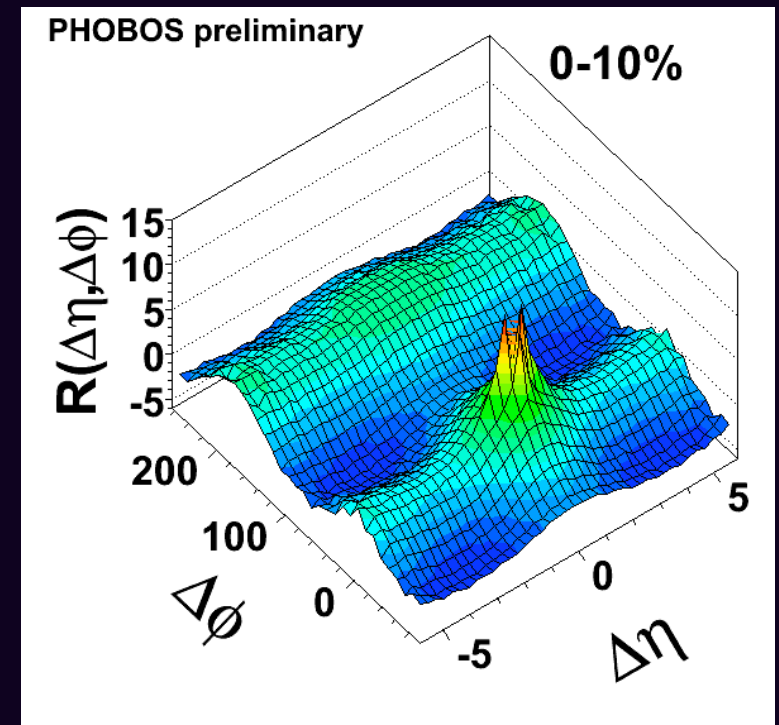
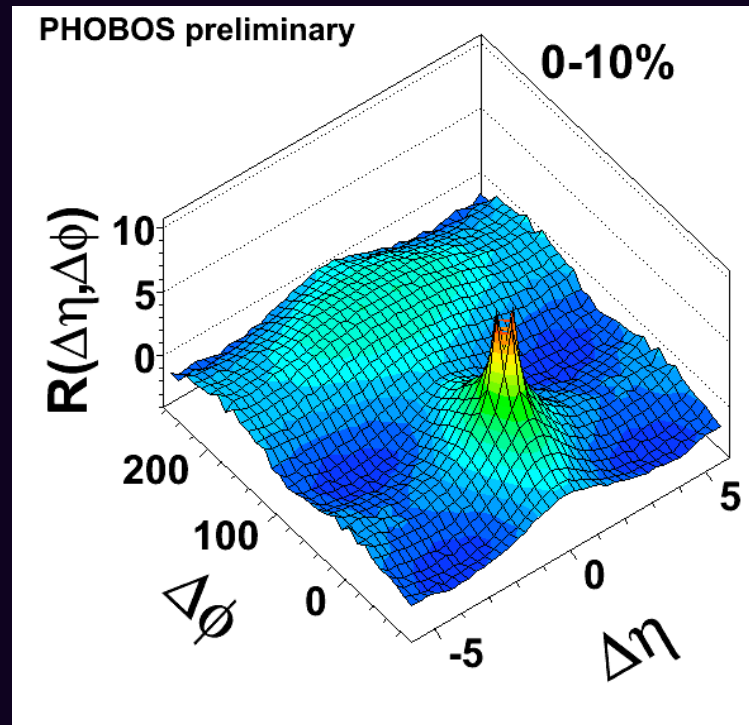
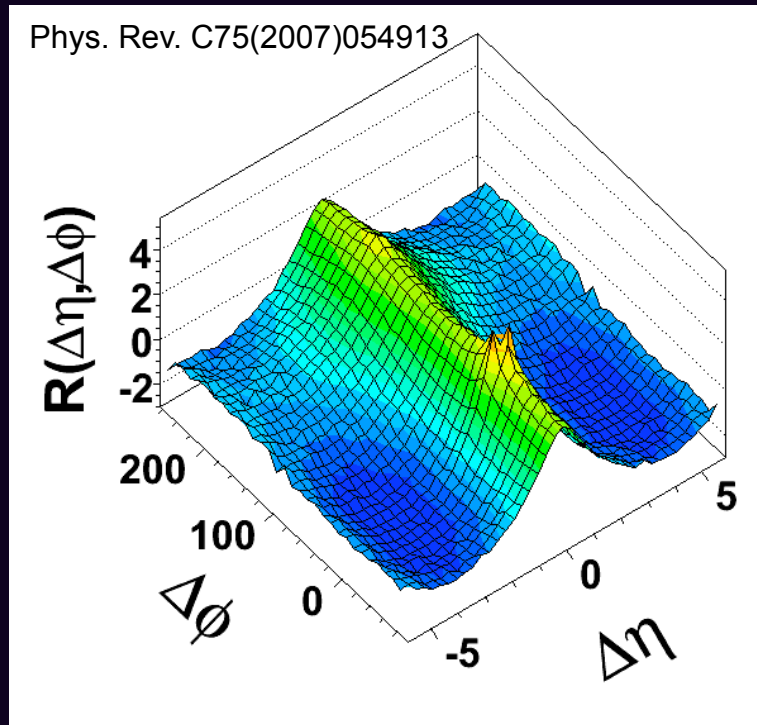
It is often said that resonances can't give a "near side" peak.

3-body decays (ω, η) do give such a peak, while 2-body decays (e.g. ρ) do not.

p_T distribution of resonances tuned to describe final state pions $dN_\pi/dp_T \sim p_T \exp(-6p_T)$



From $p+p$ to $Cu+Cu$ & $Au+Au$

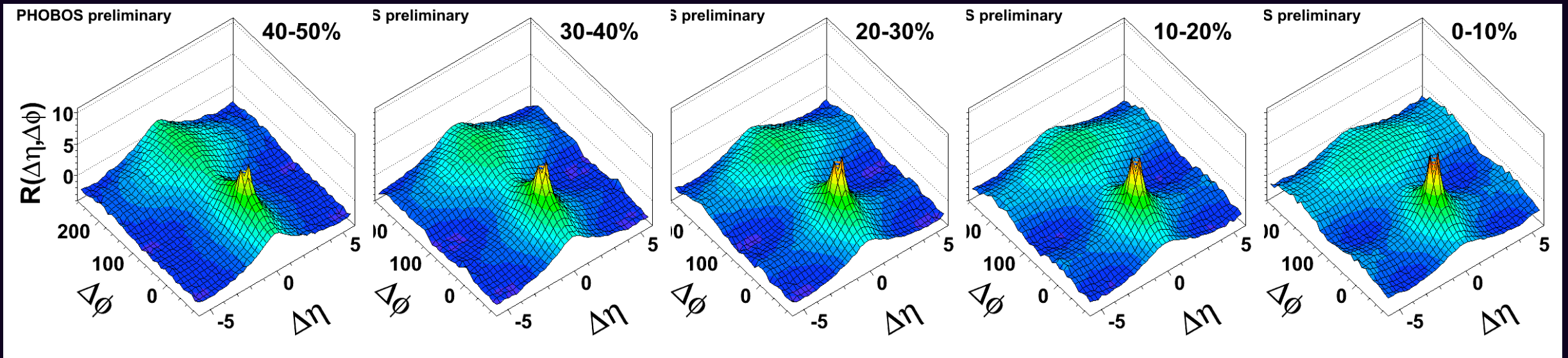


PHOBOS has extended study of 2D CF to $Cu+Cu$ and $Au+Au$ as a function of centrality

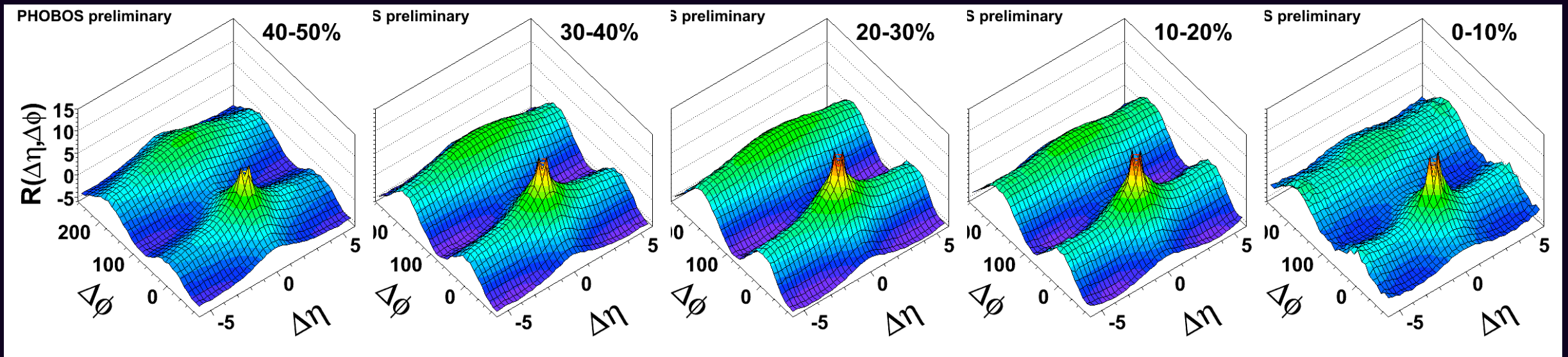
Nontrivial due to larger occupancies, but effects under control (fits to dE/dx , not counting hits)

Centrality Dependence in Cu & Au

Cu+Cu

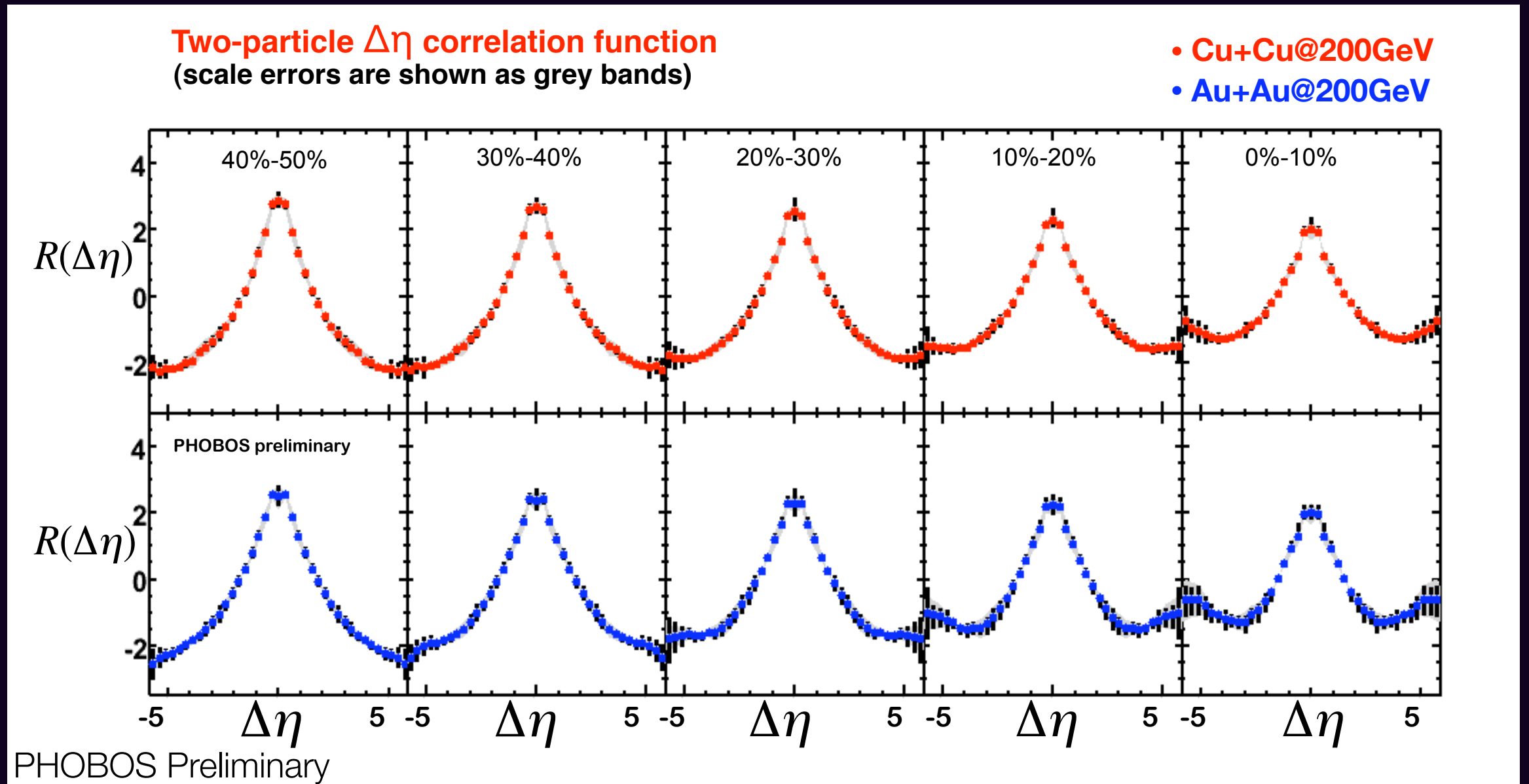


Au+Au



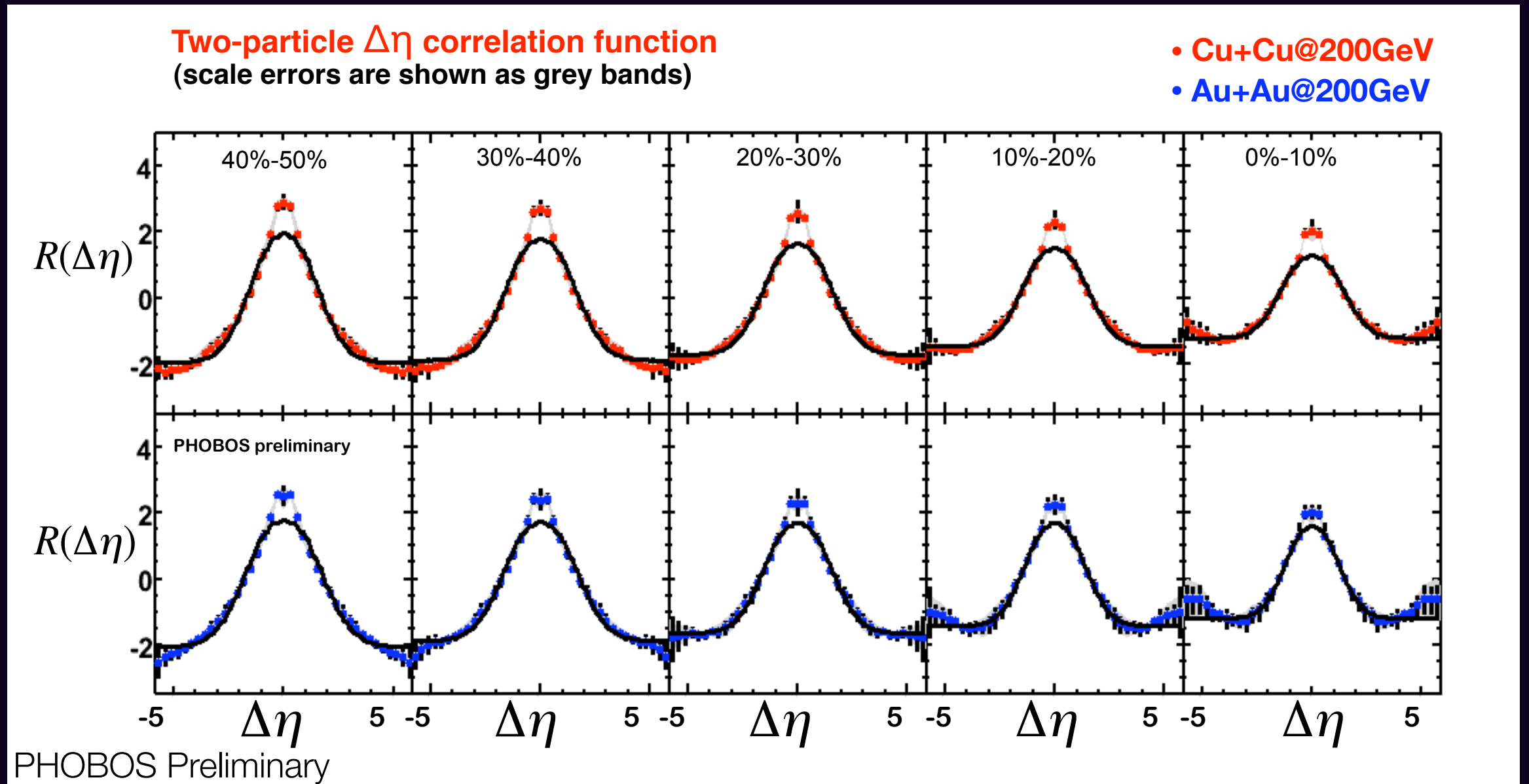
The observed long structure in $\Delta\eta$ is not a ridge.
 Rather, it is the v_2 component, which scales as $\langle 2(N-1)v_2^2 \rangle$
 (where Cu+Cu and Au+Au overlap in N , v_2 is different!)

One-Dimensional CF in Cu & Au



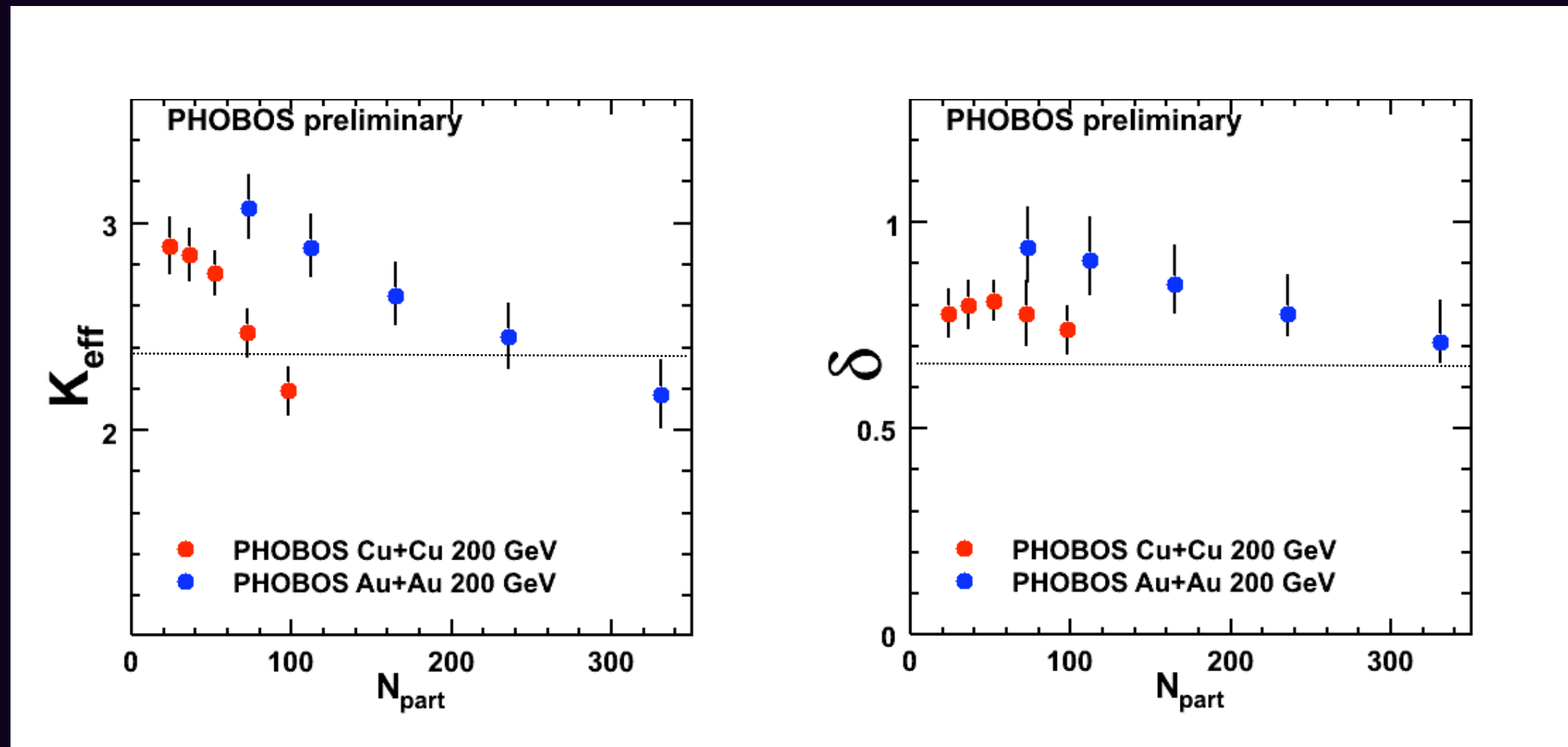
Integrating over $\Delta\Phi$ automatically integrates out v_2
Immediately see that correlation strength decreases with centrality

One-Dimensional CF in Cu & Au



Cluster fits have been performed for all bins
to quantify parameters vs. centrality

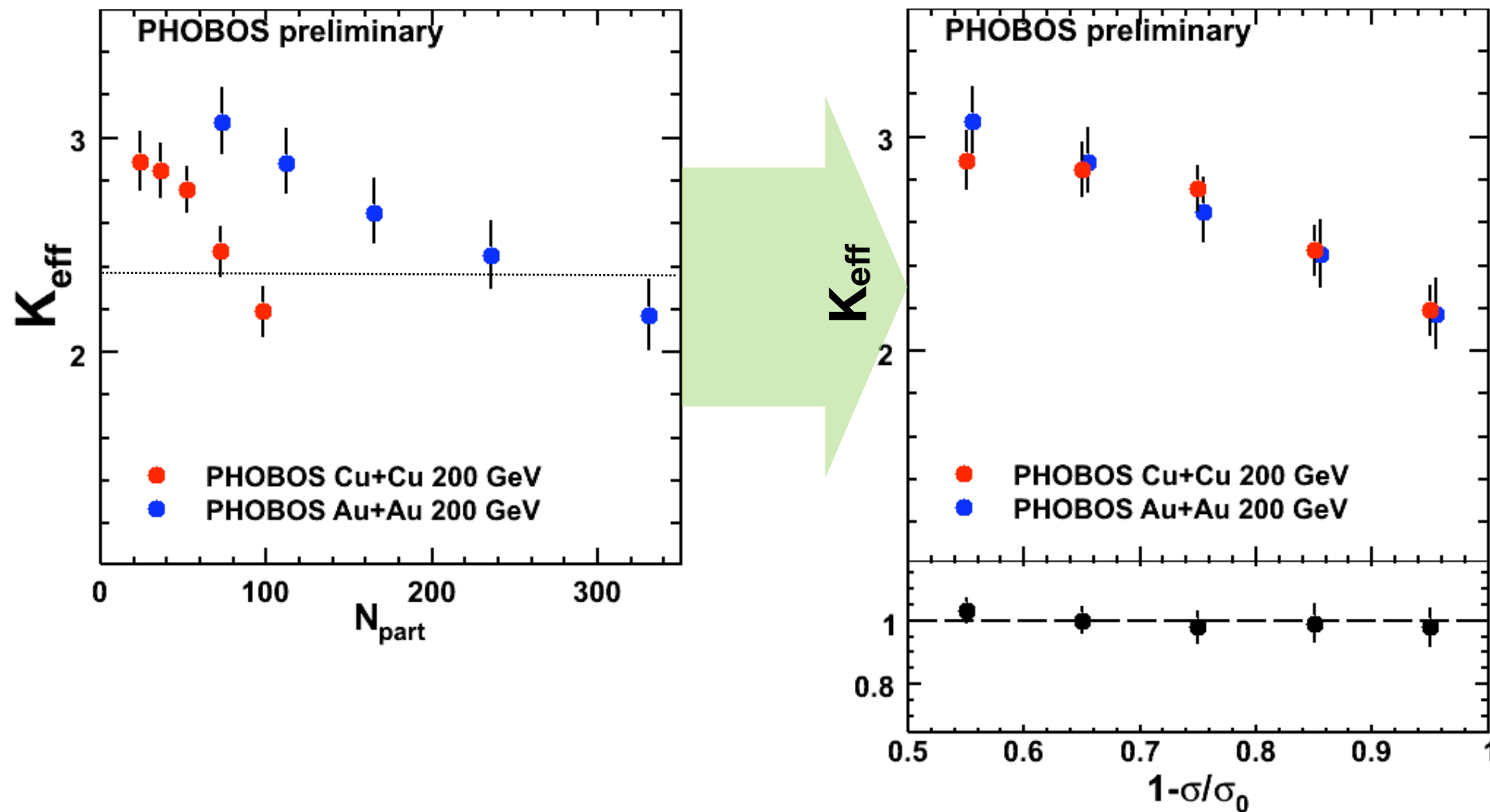
Centrality Dependence of Cluster Parameters



The first big surprises in Cu+Cu & Au+Au

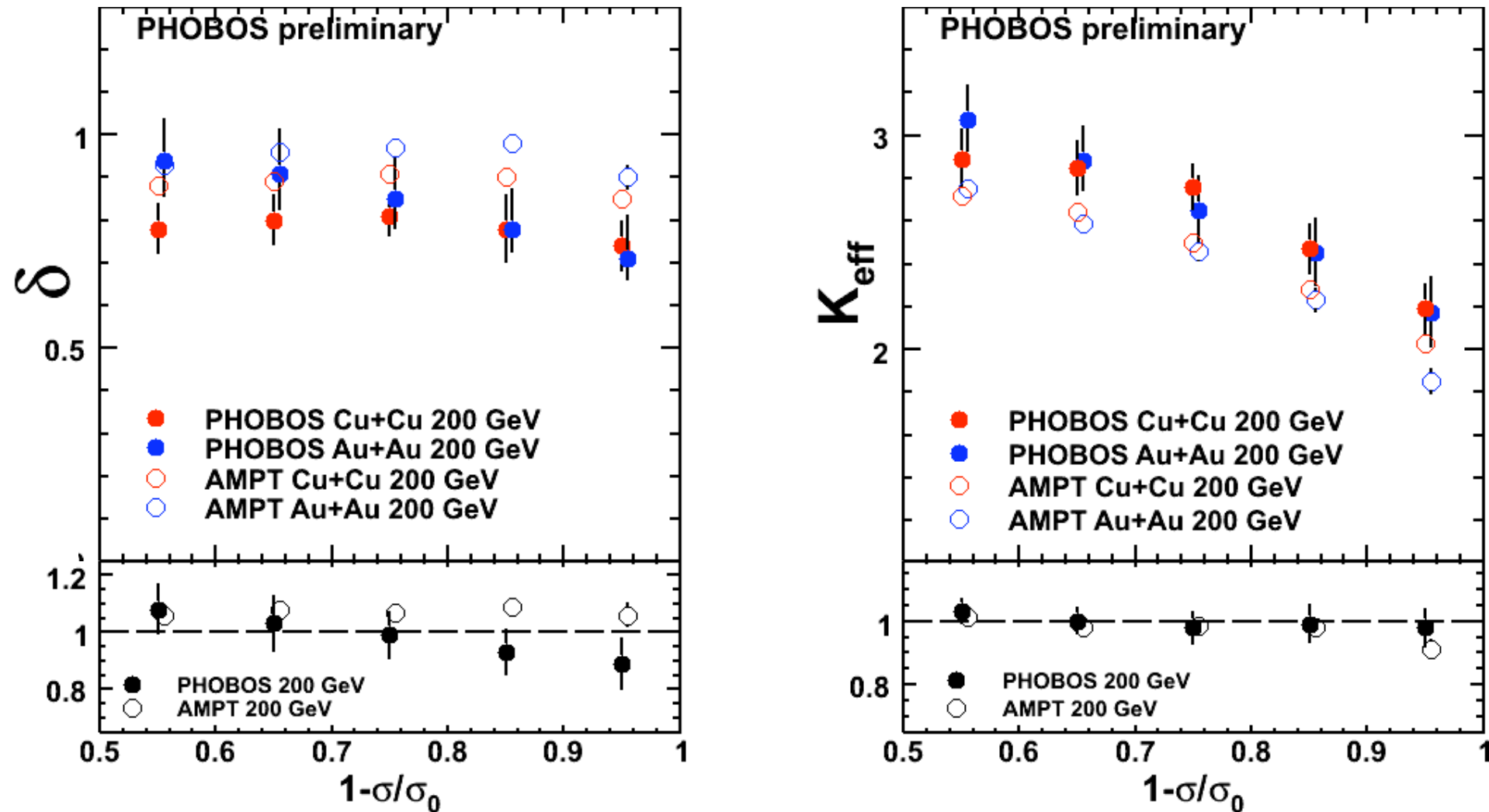
1. Peripheral events have K_{eff} much higher than p+p (a jump?)
2. Central events are only a bit lower than p+p
3. The peripheral events are “elongated” in $\Delta\eta$ (large δ)

"Geometric Scaling" in $A+A$



The next big surprise: Cu+Cu & Au+Au have the same centrality dependence vs. fraction of total cross section

Comparison to AMPT



Comparisons to standard AMPT: width and K_{eff}

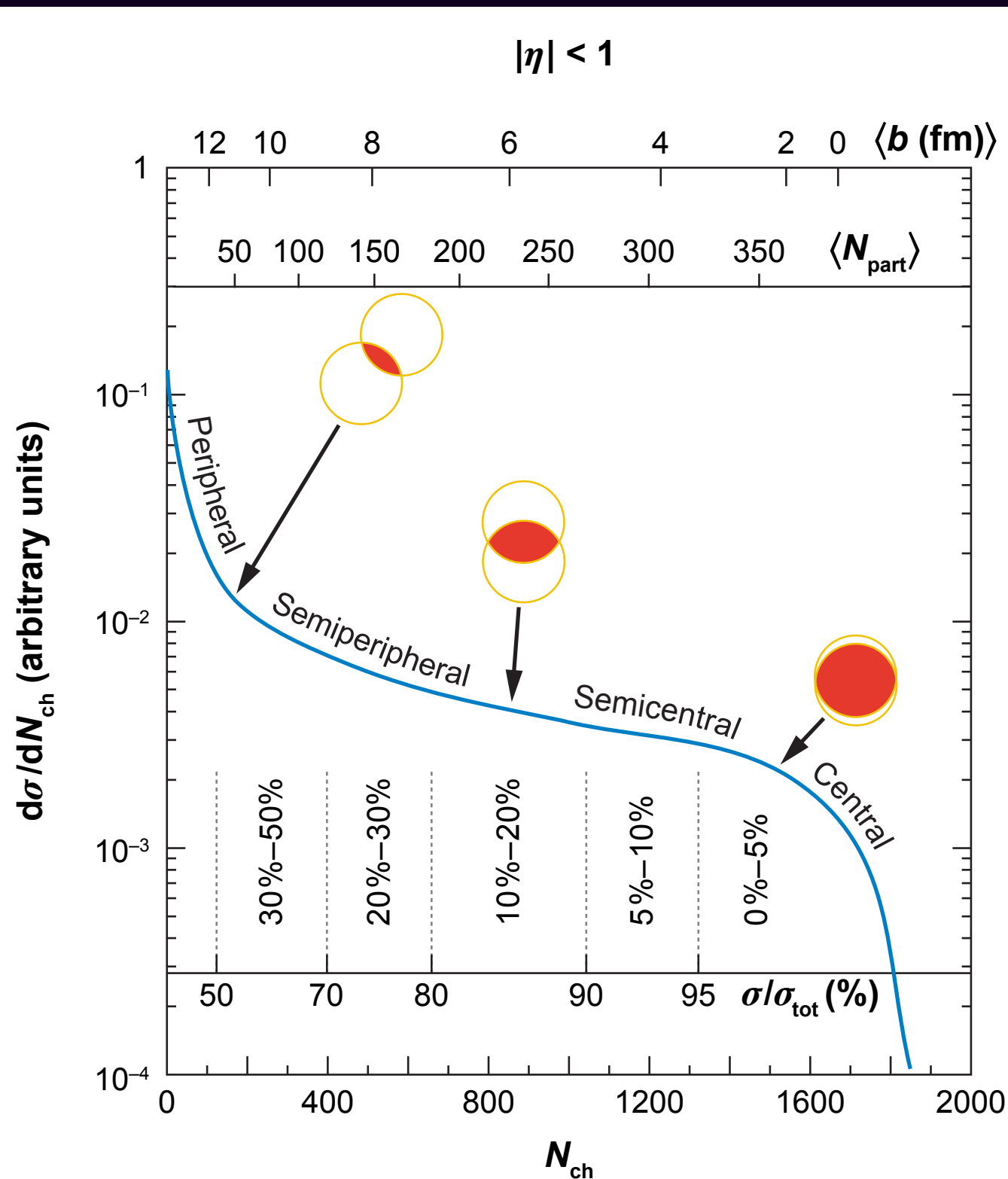
Magnitude somewhat lower, but trend is the same

"Fraction of the total Cross Section"

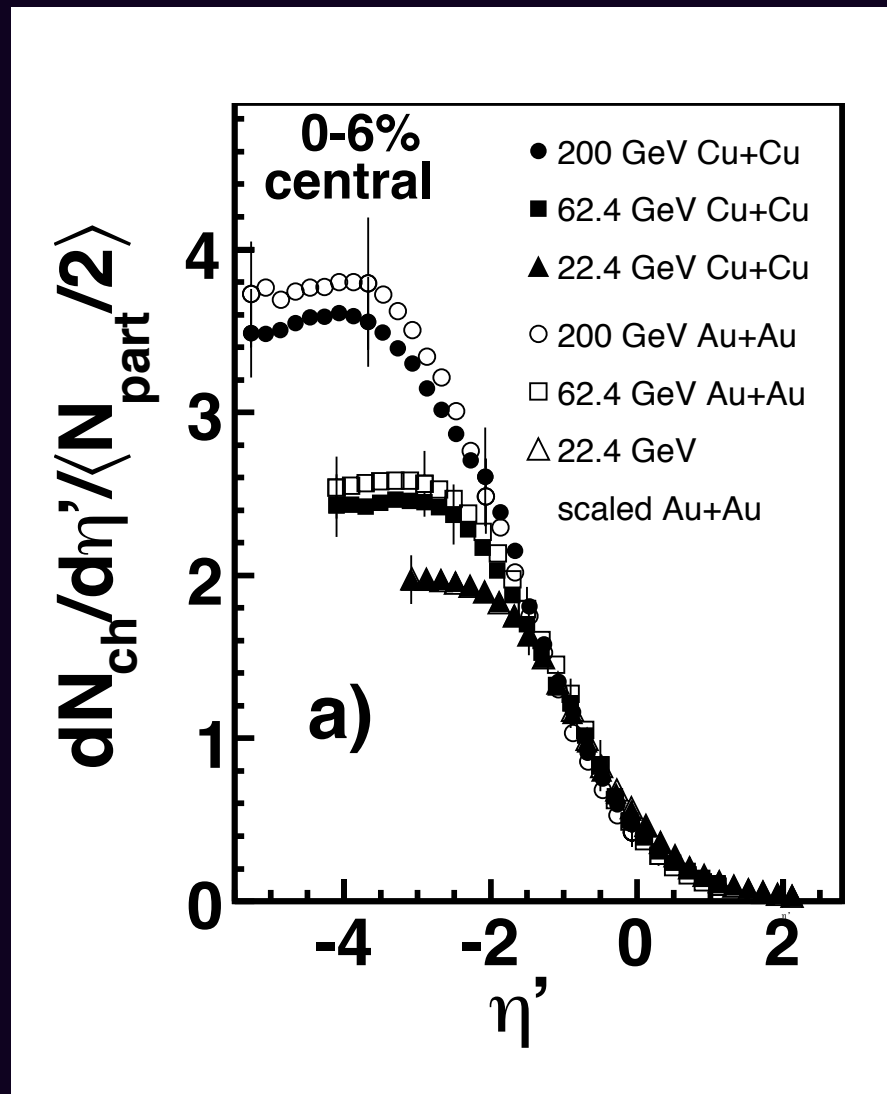
Matching systems
at the same
fraction of cross section
is like choosing same

$$\frac{b}{2R} \quad \frac{N_{part}}{2A}$$

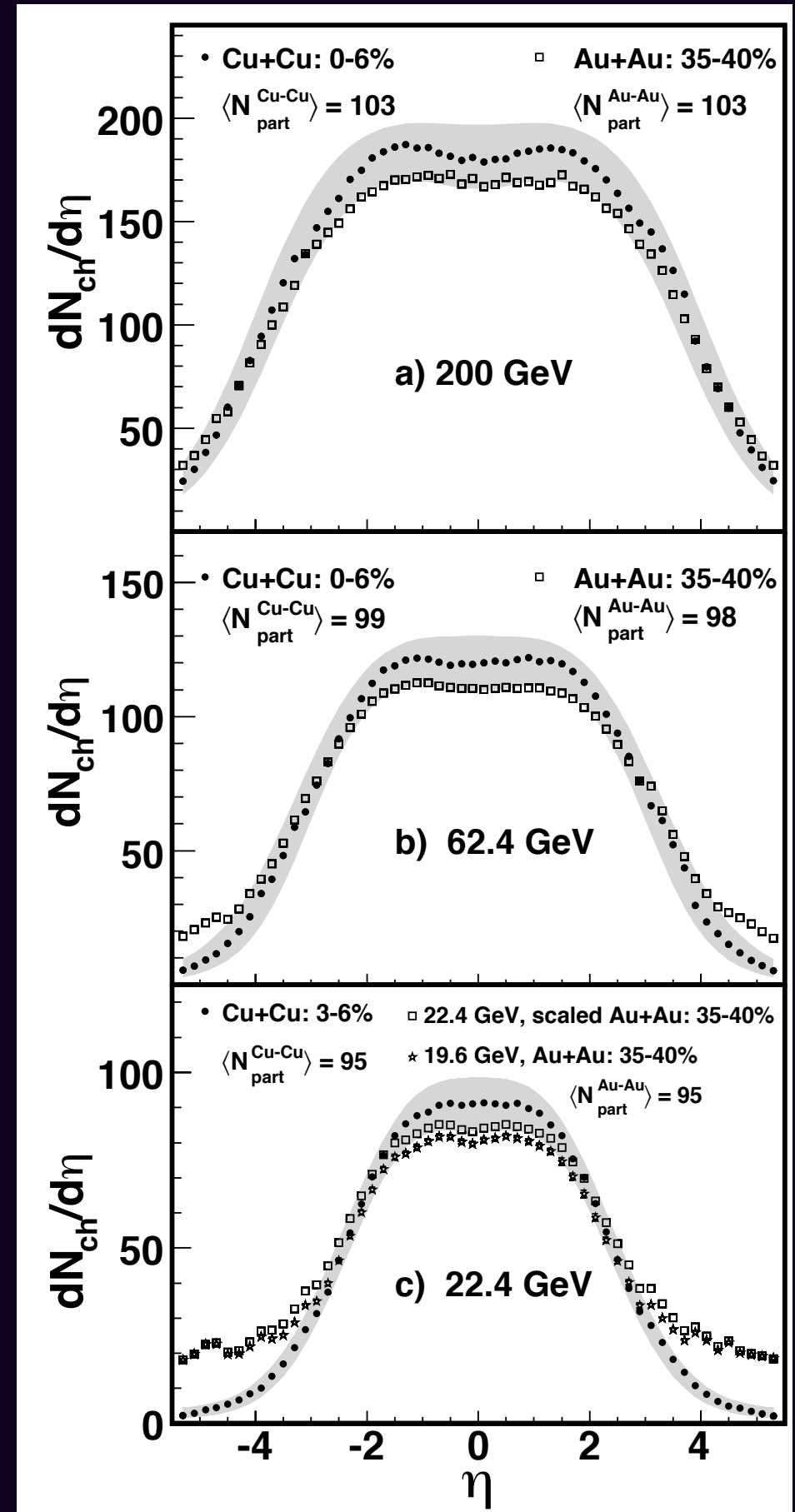
So similar geometry
(both transverse
& longitudinal)



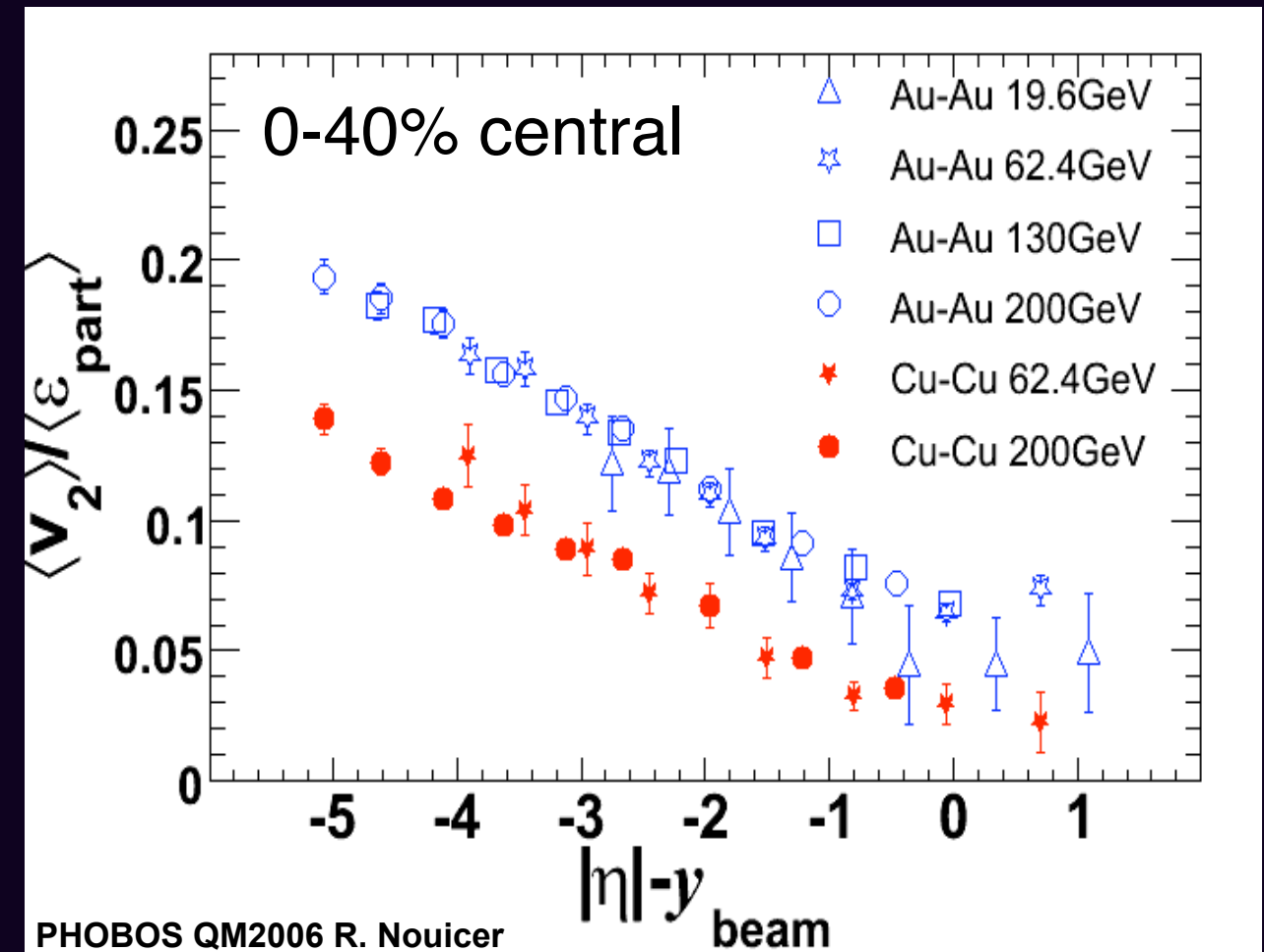
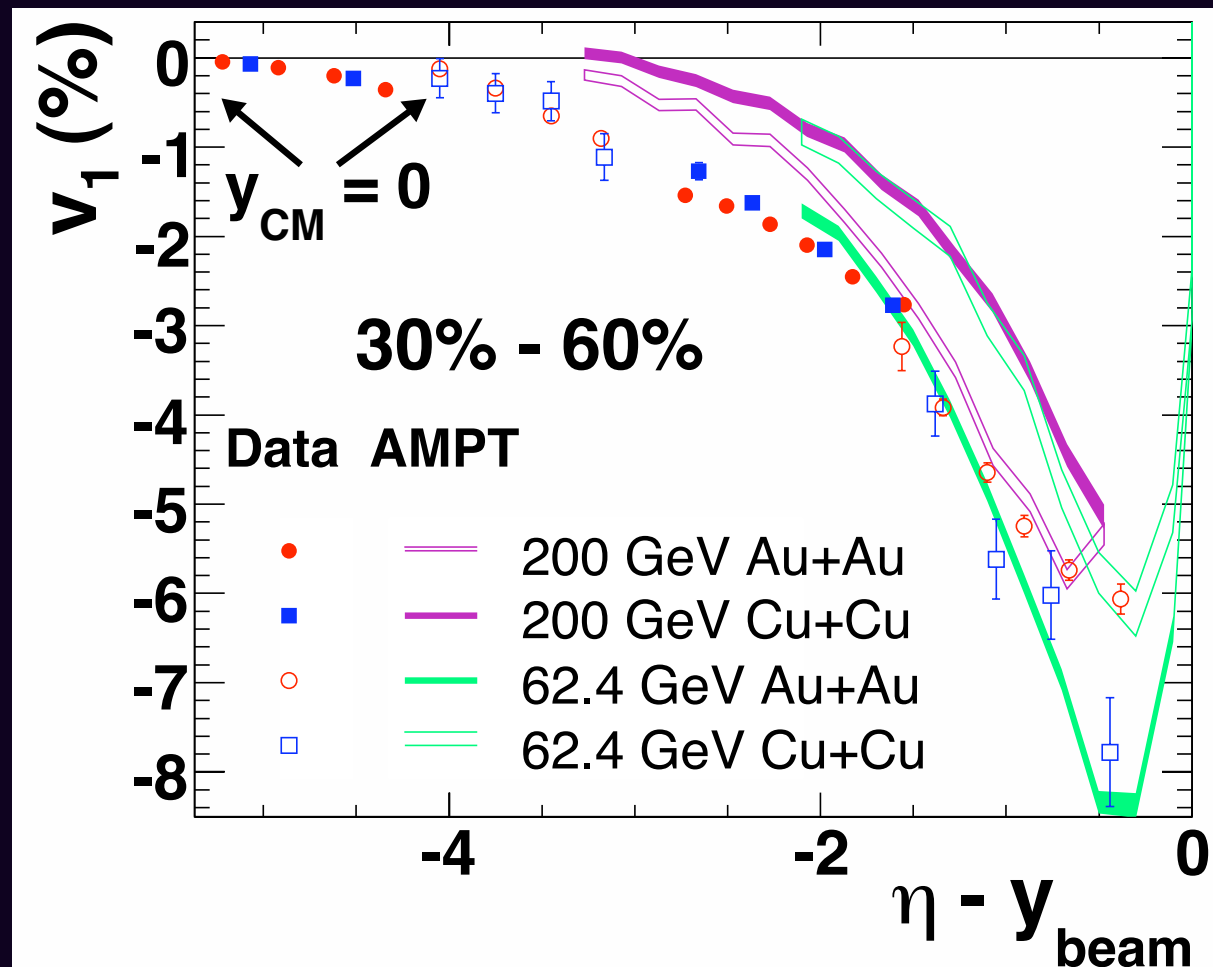
"Geometric Scaling"



$dN/d\eta$ shapes coincide
at the same centrality
(not the same N_{part})



"Geometric Scaling"

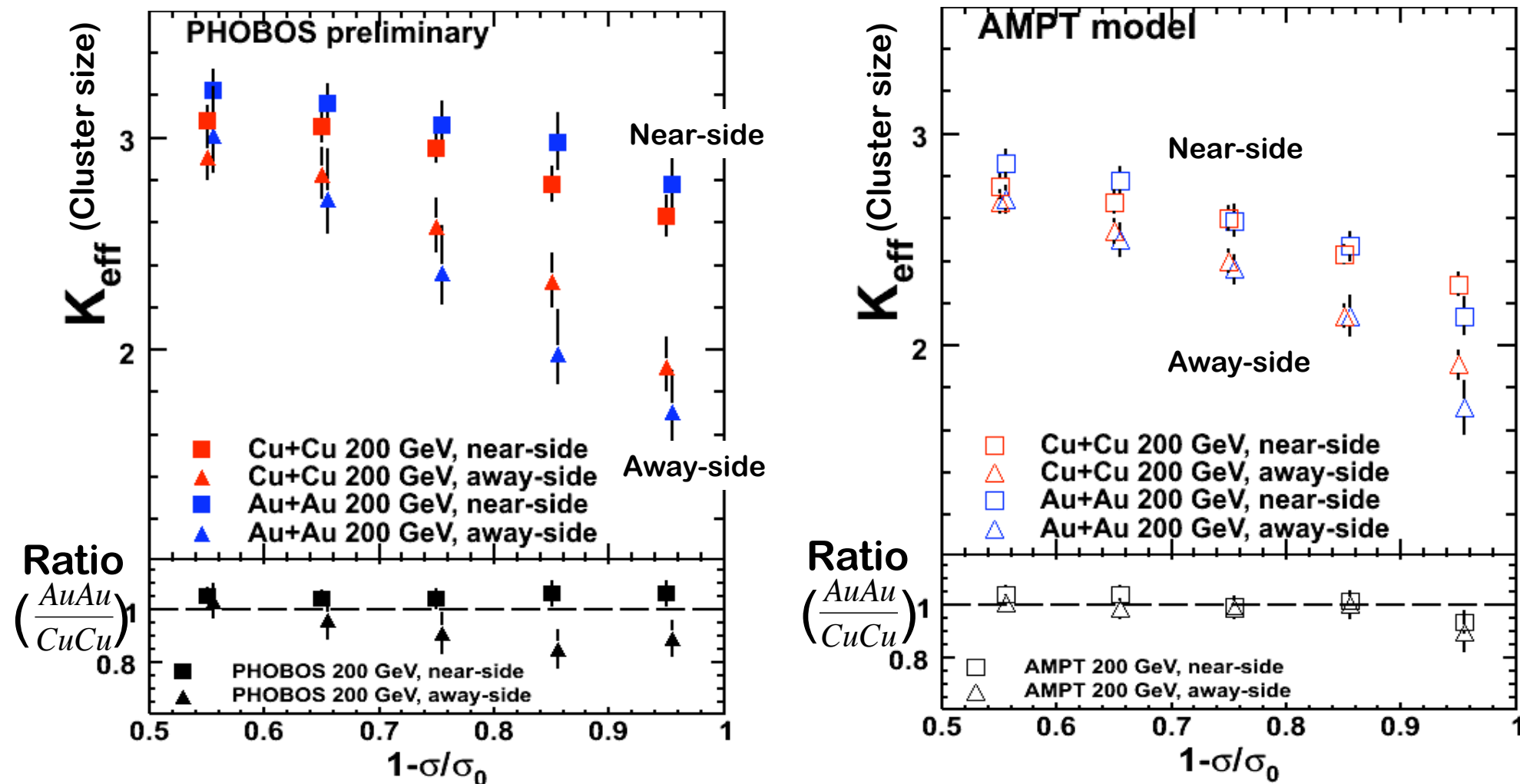


Directed flow in STAR also shows both limiting fragmentation and scales with fraction of cross section

This does not work for v_2

Various longitudinal observables scale with "fraction" of σ_{in} :
how do correlations fit in?

Near vs. Away Side (vs. AMPT)



Can split up correlation function into “near” ($\Delta\phi < \pi/2$) and “away”

Separate fits: different centrality dependence,
might breaks geometric scaling in data (but not in AMPT...)

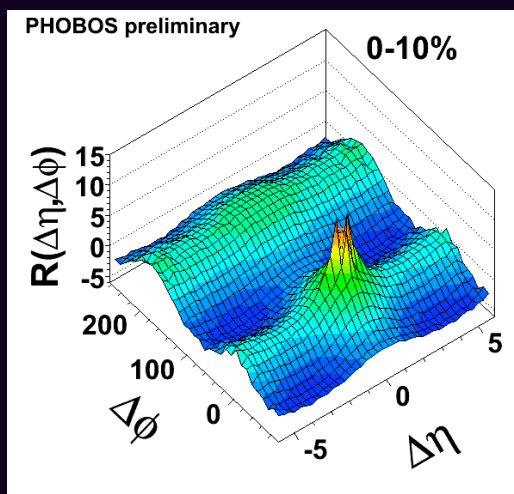
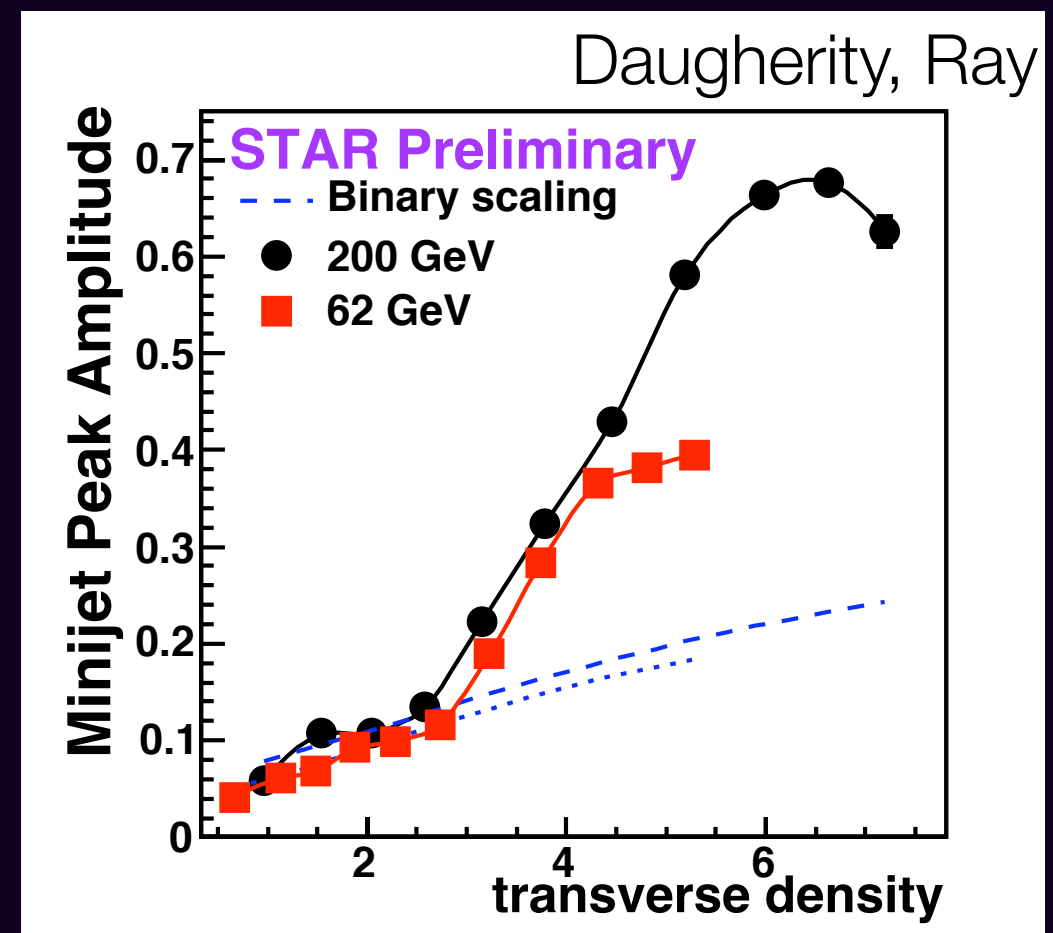
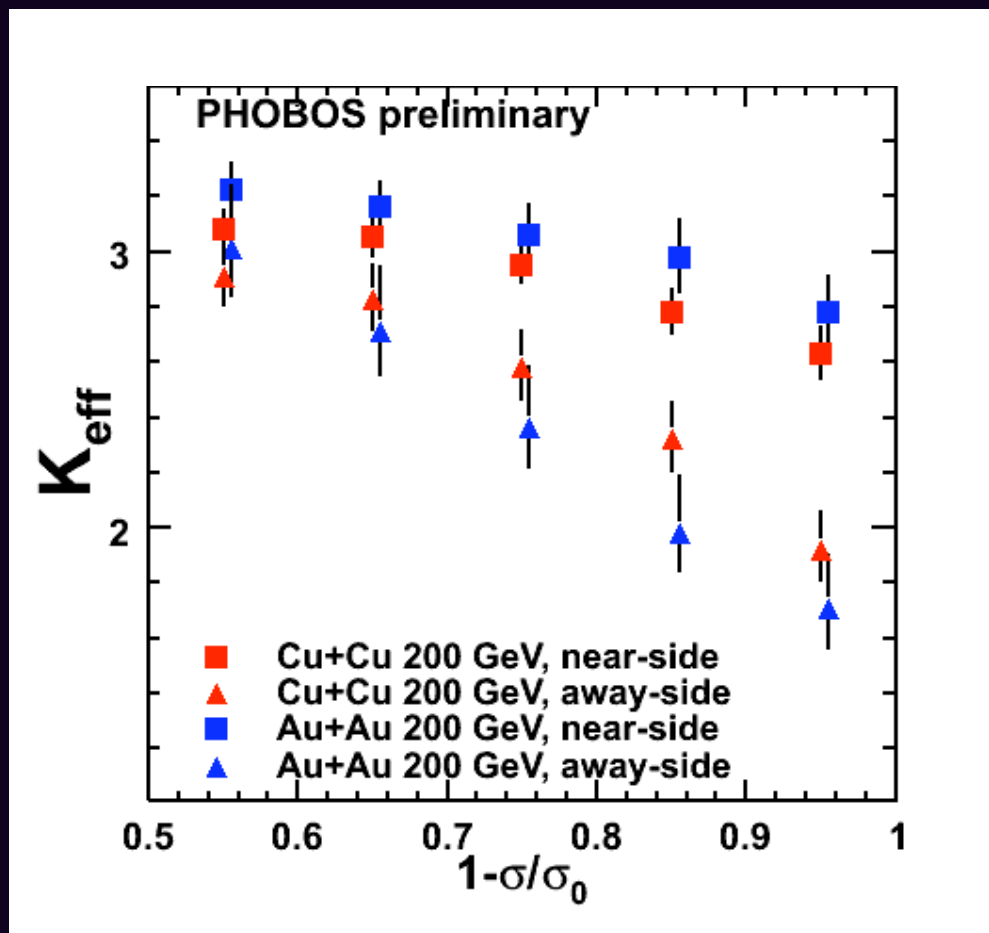


STAR

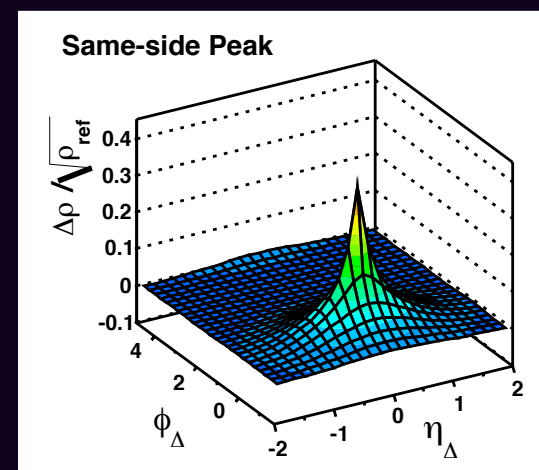
A Problem?

PHOBOS

PHOBOS vs. STAR



Smooth
decrease



Sudden
increase

The near-side seems to behave quite differently!

Definitions of Correlation Function

$$R(\Delta\eta, \Delta\phi) = \langle (n-1) \left(\frac{F_n(\Delta\eta, \Delta\phi)}{B_n(\Delta\eta, \Delta\phi)} - 1 \right) \rangle$$

PHOBOS

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \frac{F - B}{\sqrt{B}}$$

STAR?

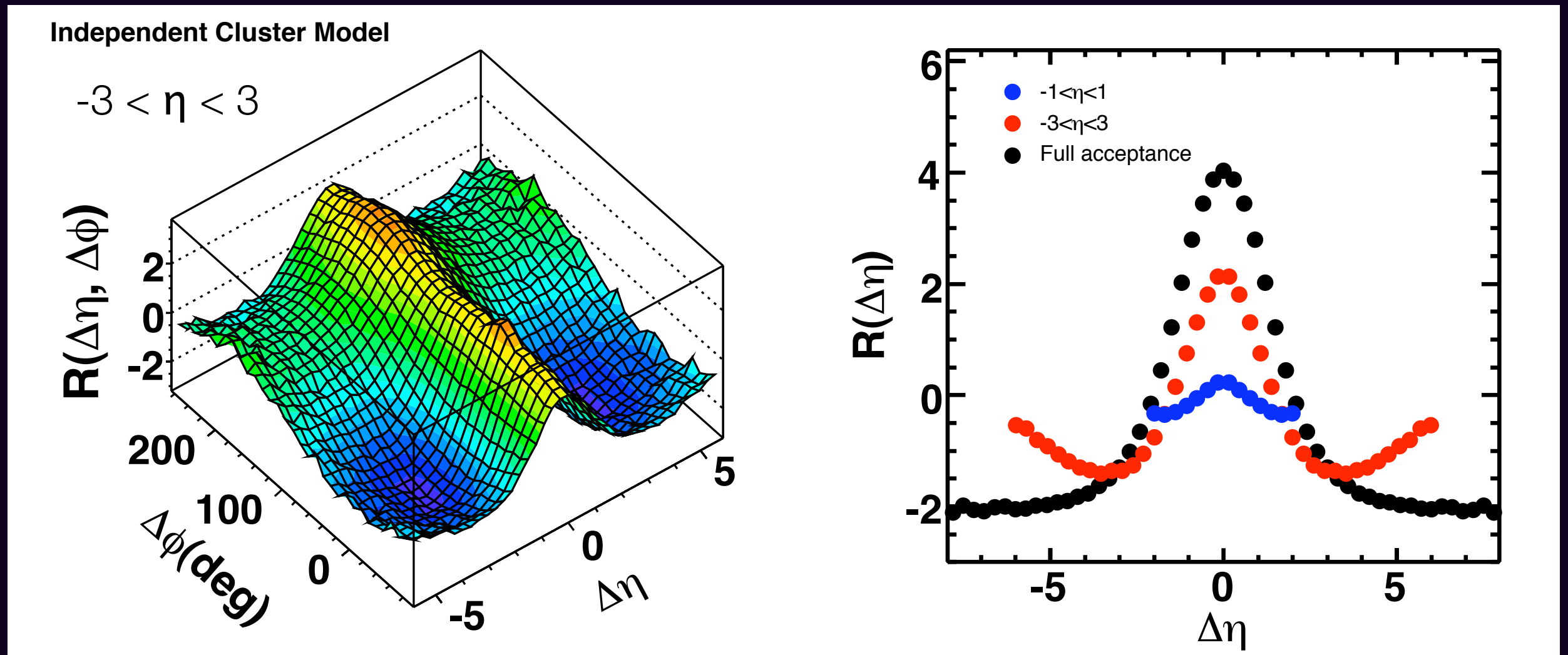
Are the two experiments using different definitions for the correlation function that give different content?

PHOBOS/UA5 cluster fit $R(\Delta\eta) = \alpha \left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1 \right]$ specifically for UA5 definition.

PHOBOS data is consistent with previous results

Same true for STAR? I can buy that $\sqrt{B} \sim n \dots$

Acceptance Matters



Same cluster model: different maximum η acceptance

Acceptance can change correlation strength & width:
However, centrality dependence should not be affected unless
width is a strong function of centrality.

Conclusions

- **PHOBOS has measured inclusive 2-particle correlations in p+p, Cu+Cu, and Au+Au**

- **Interpretation in terms of cluster model**

Decrease of cluster size with centrality

Geometric scaling between Cu+Cu and Au+Au

Central A+A is most like p+p, not semi-peripheral A+A (which is both larger and longer than p+p!)

- **How do we understand the difference in centrality dependence between STAR & PHOBOS?**

Definition of CF? Acceptance?

STAR could integrate over full acceptance and do centrality dependence!

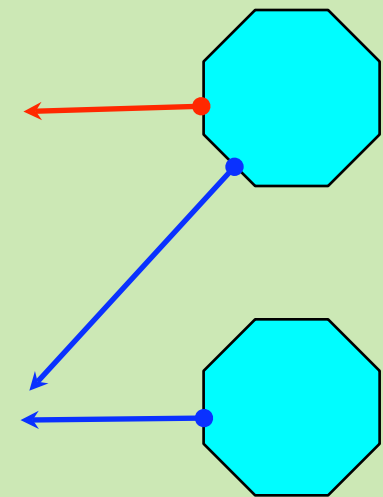
Methodology

Two particle correlation function (UA5 definition)

$$R(\Delta\eta, \Delta\phi) = \langle (n-1) \left(\frac{F_n(\Delta\eta, \Delta\phi)}{B_n(\Delta\eta, \Delta\phi)} - 1 \right) \rangle$$

$$F_n(\Delta\eta, \Delta\phi) : \rho_n^{II}(\eta_1, \eta_2, \phi_1, \phi_2) = \frac{1}{n(n-1)\sigma_n} \frac{d^4\sigma_n}{d\eta_1 d\eta_2 d\phi_1 d\phi_2}$$

$$B_n(\Delta\eta, \Delta\phi) : \rho_n^I(\eta_1, \phi_1) \rho_n^I(\eta_2, \phi_2) = \frac{1}{n\sigma_n} \frac{d^2\sigma_n}{d\eta_1 d\phi_1} \frac{1}{n\sigma_n} \frac{d^2\sigma_n}{d\eta_2 d\phi_2}$$



This definition is often used in the literature.

Ratio of F and B cancels detector/acceptance systematics